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An optimization approach for long term investments planning in energy

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HIGHLIGHTS

- Multiperiod optimization model for investments plan in energy sources.
- Investments on renewable and non-renewable energy sources are included in the model.
- Objective function is the maximization on Net Present Value.
- Capability to assess and plan the evolution of the energetic matrix at different circumstances.

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ABSTRACT

This paper presents a mathematical programming model for planning investment in energy sources. The problem formulation considers the use of renewable and not renewable sources and demands, revenues, operation, start-up, and amortization costs of new energy facilities and the amount of reserves of fossil fuels. The objective is the maximization of the Net Present Value (NPV) in the time horizon. The results provide the visualization of the investments made: time periods in and their amounts and also how the energy matrix is affected by those investments. In particular the model was applied to Argentina. The most important feature of the model is the ability to assess and to plan the evolution of the energetic matrix at different circumstances.

1. Introduction

The use of renewable sources for energy production is becoming a key issue for the future of every country. The main reasons to analyze the production of energy by means of renewable sources are the high dependency in fossil fuels for transport, electricity, heating, etc., the global warming as a consequence of using these fuels, its constant price raise and the uncertainty and limitation of world reserves levels. About 10% of the world energy consumption is produced using some sort of renewable energy, taking into account in this sector the production of hydroelectricity which is the main source [1]. Many countries around the world started, several years ago, the process of producing energy using sustainable alternatives like the wind, sun, geothermal, biomass and waste; the leading countries in this issue are: United States, Germany, Spain, China, India, Brazil and Japan. Considering that the consumption of energy increases every year following the population growth; and the oil, gas, carbon and uranium reserves are limited, the search for sustainable alternatives is fundamental.

In the last five years, several works can be found in the literature dealing with this problem, Krajacic et al. [2] studied the production of electricity for Portugal in order to cover all the demand of this country by means of renewable energy sources (RES). They use H2RES simulation model to integrate several renewable sources (wind, solar, biomass, hydropower and ocean waves) in the energy system. They also include some sort of storage systems to accumulate energy in order to reduce the number of generation units. The authors conclude that the tool have some limitations to make the analysis, pointing out that there is no automatic optimization based on cost, environmental and social impact using this system. The 100% RES is achieved using hydropower (32%) and wind (24%), which in terms of real solution considering the cost and environmental impact, needs more insights.

The model proposed by Baringo and Cornejo [3] is a stochastic mathematical program with equilibrium constraints (a stochastic MPEC) to analyze the risk involved in wind power investments. In their proposal they consider that the wind power investment and operation have several uncertainties and risk involved such

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as: (a) the production of a wind power facility ready to operate is both variable and uncertain, (b) the wind power farm investment costs are expected to decrease while technology acquires maturity but to which extension such decrease will materialize is uncertain and (c) given the previous uncertainties the profit for a wind investor is high and thus risk management must be taken into account. They solved three illustrative examples considering three different scenarios: (1) Investment Cost Uncertainty, (2) Load Demand/Wind Power Production Uncertainty and (3) both Load Demand/Wind Power Production and Investment Cost Uncertainty. In order to test the model, they work with a Case Study based on the IEEE 118-Bus Test System which comprises 54 generating units, 99 loads, and 186 transmission lines. They conclude that the proposed model is tractable for systems of realistic size provided that the number of considered scenarios is small enough. In another work, researchers from the same group [4], proposed a bilevel model for investments decision making for a strategic energy producer. The upper-level problem represents both the investment decisions of the producer and its strategic offering corresponding to each demand block and scenario. This upper-level problem is constrained by a collection of lower-level problems that represent the clearing of the market for each demand block and scenario. The target of these lower levels problems is to maximize the corresponding declared social welfare, subject to power balances, production/demands limits and transmission constraints. With this model proposal the authors provides a methodology to assist a strategic producer in making investment decisions on power generation, they also pointed out that the resulting model, although computationally expensive, is tractable.

Connolly et al. [5] generates a model to satisfy the energy demands for Ireland by means of renewable sources. According to these authors, in Ireland 96% of the energy demand is provided by using fossil fuels, where 89% is imported. EnergyPLAN tool is used to perform the analysis and they include the electricity, heating and transport consuming sectors. The renewable sources considered in this study are biomass, solar, waves, wind and hydropower. They also increase the capabilities in the energy storage system. They propose to solve four scenarios: 1 – 100% renewable based on biomass, 2 – 100% based on hydrogen, 3 – 100% renewable maximizing the generation of electricity and 4 – a combo of the other previous three. The results obtained are very different for each scenario. The authors consider that the energy demands are frozen to year 2007 and the analysis was made based on the technical and resource perspectives not from an economical point of view. As the authors pointed out the study is useful for illustration purposes.

Pina and coworkers [6] presents a modeling framework to optimize the investment in new renewable electricity generation on the long-term horizon time for Portugal. The authors take into account the hourly dynamics of electricity supply and demand. The framework is built combining two of the most used energy planning tools, TIMES as a long-term model for the optimization of investment in electricity generation capacity and EnergyPLAN as a short-term model for optimizing the operation of the system. They claim that the combination of both tools is crucial for the development of pathways for the transition to electricity systems with high penetrations of renewable energy sources and that the proposed methodology can also be applied to study the introduction of different energy efficiency measures.

Mondal et al. [7] evaluates the strategies for future energy-supply for the United Arab Emirates (UAE) power sector. The analyses are done by applying MARKAL model. Different policies such as a CO2 emission reduction constraint, renewable energy production targets, and subsidy minimization through international benchmarking for domestic gas prices are applied for this analysis. The results show that the alternative policy scenarios directly allocate clean advanced and renewable technologies to generate electricity. These scenarios reduce CO2 emissions in power sector. The simulation results from model show that alternative sustainable energy development policies expected total system cost is not significantly higher.

Several analogous works can be found in the literature, just to mention some of them, Cosic et al. [8] analyzed the case of a 100% renewable energy system for Macedonia, Lund and Mathiesen [9] perform a similar study for Denmark and Mason et al. [10] evaluate the case for New Zealand.

Reading those works, it can be seen that several criteria are used to study an energy system based on renewable sources. The criteria selected to perform the study is fundamental in order to make the right decisions. Ostergaard [11] evaluates a set of optimization criteria applied to an energy system model of Western Denmark; some of them were technical and others economical. The most used in the literature are: renewable energy shares, carbon dioxide emissions, economic costs, societal costs, energy costs and total costs.

Energy production meets the challenge of satisfying ever-increasing demands with traditional resources decreasing and the consequent requirement of incorporating new sources. New tools are needed in order to harmonize, integrate the different requirements, resources and capacities. In this work, a MILP (Mixed Integer Linear Programming) formulation is presented to analyze the planning of investments and operation of different energy sources. The proposed model allows to attain different objectives. First, the different energy sources are simultaneously taken into account, including renewable ones. The objective of this study is to handle renewable energy in combination with non-renewable ones in order to extend the life of natural resource reserves. For the next decades, the energy supply will be reduced from fossil fuels and depends on a higher proportion from renewable sources. Thus, a mathematical analysis tool is required to effectively assess the trade-offs about them, considering different aspects as investments, resources availability, operation, setup, amortization, etc. Second, the formulation adopts a multiperiod representation that enables the evaluation of the evolution of the different performance indicators along the time horizon. Also, the time required to start the operation of the new facilities from the moment the corresponding investment is decided, as well as the amortization value are taken into account. From the modeling point of view, the model proposes a formulation based on disjunctive programming that allows an appropriate representation of the alternatives considered in the problem. The model is solved in reasonable computation times and, thus, different scenarios can be easily assessed.

Although the proposed formulation is posed for Argentinean case taking into accounts the renewable energy sources that better adapt to Argentina, this model can be applied to any country or region. Also, the parameters adopted in the examples of this work can be adjusted to specific cases, for example: time horizon, energy sources, demands, economic parameters, etc.

The remainder of this paper is structured as follows. First, the addressed problem is described and the main assumptions are introduced in Section 2. Then, in the subsequent section, the proposed formulation is presented. Finally, in Section 3 several scenarios are considered to demonstrate the capabilities of the proposed approach in order to evaluate an energy system.

2. The model

The composition of the energy matrix in Argentina is shown in Fig. 1; data is extracted from Argentina's Energy Agency (Secretaría de Energía de la República Argentina, 2007). It can be observed that

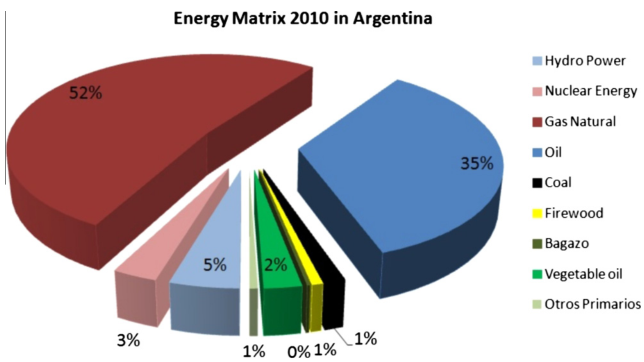

Fig. 1. Energy Matrix [20].

the main sources are natural gas and oil, 49% corresponds to natural gas and 41% oil, then 4.5% hydropower, 2.5% nuclear, 1.9% biomass and 0.8% other sources. Looking at this figure it can be easily concluded that the use of sustainable ways of producing energy is essential for the future of the country, especially considering that Argentina has an important amount of renewable natural resources. In recent years, there has been an effort to change the matrix structure by employing sustainable energy, like wind power [12], hydro-kinetic turbines [13–16], biofuels (bioethanol and biodiesel) [17,18] and nuclear plants [19]. There has been also a market penetration of solar collectors for housing and commercial heating.

This work proposes a multiperiod disjunctive optimization model to maximize the Net Present Value (NPV) of the energy sources (renewable and non-renewable) in order to satisfy a 100% of the energy demands for Argentina. The model takes into account three sectors:

1. different energy sources that include collector plants,
2. processing plants that transforms this sources in a form of usable energy (electricity, fuel),
3. the final consumers where residential and industrial sectors are involved.

This situation is described in Fig. 2 where the paths between sources and consumers are shown. For example, the soybean seeds are collected in farms, then goes to a biodiesel plant (mainly producers of soybean oils), from this point goes to a petroleum refinery where the biofuel is mixed in a proportion up to 20% with diesel and then is commercialized to the consumers.

The energy sources included in this model are: oil, gas and uranium as non-renewable and biomass, wind, solar and hydropower as renewable sources. Transformation plants cover petroleum refineries, nuclear plants, thermoelectrical plants, wind power farms, ethanol and biodiesel refineries, hydro-kinetic turbines farms and solar collectors for heating.

In the consumers sector, we include industrial and residential electricity demands, diesel and gasoline fuels for transportation and domestic consumes, gas for commercial and residential heating. The demand values used corresponds to year 2010 taking the values reported by Argentina's National Agencies [21–25]. Since we consider a multiperiod model until year 2030, the demands were estimated and actualized using a constant rate value that considers an average of the demand increase in the last years.

A key factor in developing the model presented in this work is the use of generalized disjunctive programming [26–28]. As regards modeling, disjunctive programming facilitates the representation of complex situations involving multiple decision levels in a very simple way, giving a model easy to understand [29]. A generalized disjunctive programming model takes the following form (1):

$$
\begin{aligned}
&Min \quad z = \sum_{k\in K} c_k + f(x)\\
&s.t. \quad r(x) \leqslant 0\\
&\quad \bigvee_{j in J_k} \begin{bmatrix} Y_{j,k} \\ g(x) \leqslant 0 \\ C_k = \gamma_{j,k} \end{bmatrix} \quad \forall k \in K\\
&\quad \Omega(Y_{j,k}) = True\\
&\quad x \geqslant 0, \quad c_k \geqslant 0, \quad Y_{j,k} \in True, False
\end{aligned}
\tag{1}
$$

In this model, $x \in R^n$ is the continuous variables vector and $Y_{j,k}$ are Boolean variables. $c_k \in R^1$ are continuous variables and $\gamma_{j,k}$ are values that correspond to the evaluation of alternatives $f: R^n \to R^1$ is the term of the objective function that depends on variables x and $r: R^n \in R^q$ are a general set of constraints that do not depend on disjunctions. This general model assumes that $f(x)$ and $r(x)$ are convex functions. A disjunction is composed by a set of terms linked by the logical OR operator. In each term of the disjunction there is a Boolean variable $Y_{j,k}$, a set of convex constraints $g_{j,k}: R^n \in R^p$ and a cost variable c_k. If the Boolean variable $Y_{j,k}$ is true, then conditions $g_{j,k}(x) \leqslant 0$ and $c_k = \gamma_{j,k}$ must be met. Otherwise, if $Y_{j,k}$ is false, the corresponding constraints are ignored. It is assumed that each term of the disjunctions gives rise to a non-empty feasible region. Finally, $\Omega(Y) = True$ is a set of logical constraints generated by using the set of Boolean variables Y.

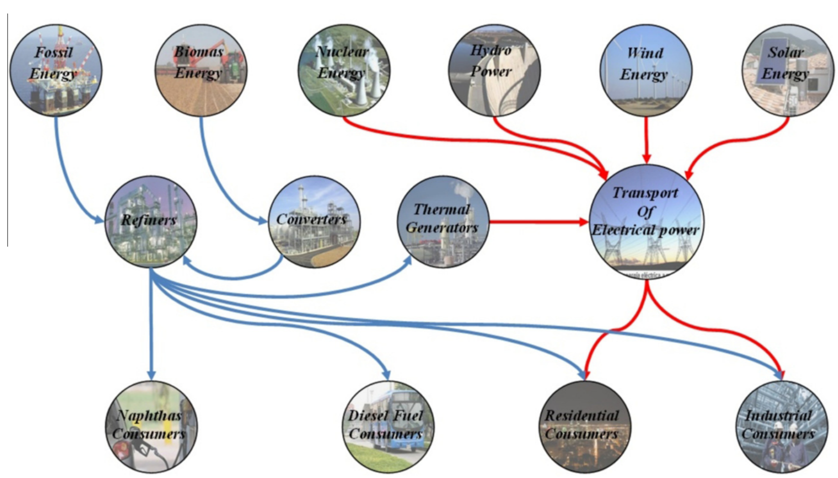

Fig. 2. Energy production from sources to consumers.

2.1. Objective function

The objective function selected is the maximization of the Net Present Value (2) over the time horizon considered (years 2010–2030). The Net Present Value (NPV) allows the calculation to the present of future investment cash flows. The NPV consists on the actualization at time 0 of future investments by using an actualization tax. The procedure is linear and very simple to implement. It gives important economic information in terms of the amount of money needed to invest at the present moment. The difficulty of the NPV is how to determine the discount tax because sometimes is not clear the best value for it. Another issue in this type of problems is that it only considers economic aspects of the investments, which is a very important issue, but for energy and renewable sources some other goals must be taken into account like environmental and social impacts. This inclusion of these aspects is part of the future work.

$$NPV = \sum_{\substack{i \in Markets_{i,k} \\ k \in Markets_{i,k} \\ t}} \frac{((1-NT)\cdot CSF_{i,k,t} + NT \cdot CA_{i,k,t})}{(1+TI)^{t-1}} \tag{2}$$

where

$$CSF_{i,k,t} = (P_{i,k,t} - CO_{i,k,t})\cdot x_{i,k,t}\cdot hr - CI_{i,k,t} - CS_{i,k,t}\cdot ICap_{i,k,t} \quad \forall t; \quad \forall (i,k) \in Markets_{i,k} \tag{3}$$

In Eq. (2), NPV corresponds to the Net Present Value, which is equal to the updated amount of all cash flows $CSF_{i,k,t}$ over every period t, for every energy source i and market k linked by the subset $Markets_{i,k}$. This term is multiplied by $1-NT$ which represents the factor that affects the revenues because of taxes. In the second term $NT \cdot CA_{i,k,t}$ represents savings in taxes because of depreciation, where NT is the tax payed and CA is the depreciation cost of the installation for source i, market k, period t. For Argentina the annual amortization ($CA_{i,k,t}$) cost is calculated as 85% of the investment divided over the lifetime years of the plant.

In Eq. (3) we express each cash flow $CSF_{i,k,t}$ like the annual financial balance. The term $P_{i,k,t}\cdot x_{i,k,t}$ represents the revenues obtained by the source i, market k, period t, where P is the sale price and x the amount sold, the term $CO_{i,k,t}\cdot x_{i,k,t}$ corresponds to the operating cost of the energy system (new and old plants). This term is the product of the individual operating cost ($CO_{i,k,t}$) multiplied by the capacity of the plant for source i, market k, period t ($x_{i,k,t}$) and the annual operation hours of the plant (hr) which is a parameter, $CI_{i,k,t}$ is the investment cost for a new installation of the source i, for market k, in period t. The start-up cost of a new installation (considered only once in the life of a new plant) is expressed by the product between the individual cost $CS_{i,k,t}$ multiplied by the new plant capacity $ICap_{i,k,t}$ for source i, market k, period t.

2.2. Investment decisions

The investment in new energy sources is modeled using disjunctive programming [30] (DP). Two decisions levels are introduced: the first one selects if the investment in source i is made or not, while the second involves its magnitude in terms of capacity and hence the money needed for it. Disjunction (4) formulates these decisions. For source i, market k in period $t-T_{i,k}$, when Boolean variable $w_{i,k,t-T_{i,k}}$ is true, it indicates that new investment is performed. Note that the difference between $t-T_{i,k}$ represents the gap between the time you decide to make the investment t and the moment the plant start its production $T_{i,k}$. When this Boolean variable is false, no investments are required. In the first case, once the investment decision has been made, a second level of embedded decisions is introduced to select the capacity of the new facilities. This decision is handled by the Boolean variable $y_{r,i,k,t-T_{i,k}}$, selecting different capacity ranges from the set R. Note that in this case, only one term must be true, only one element of the set R will be selected. $ICap_{i,k,t}$ indicates that the plant capacity is restricted by the parameter $Imax_{r,i,k}$, which is a maximum value for that term; similarly $CI_{i,k,t-T_{i,k}}$ is a variable that specifies the investment, also limited by a minimum for that term $Cm_{r,i,k}$.

$$\left[\begin{array}{c} w_{i,k,t-T_{i,k}} \\ \bigvee_{r=1..R}\left[\begin{array}{c} y_{r,i,k,t-T_{i,k}} \\ CI_{i,k,t-T_{i,k}} \geqslant Cm_{r,i,k} \\ ICap_{i,k,t} \leqslant Imax_{r,i,k} \end{array}\right]\end{array}\right] \vee \left[\begin{array}{c} \neg w_{i,k,t-T_{i,k}} \\ CI_{i,k,t-T_{i,k}} = 0 \\ ICap_{i,k,t} = 0 \end{array}\right] \quad \forall t > T_{i,k}; \quad \forall (i,k) \in Markets_{i,k} \tag{4}$$

2.3. Oil fuels

Eq. (5) defines the amount ($q_{i,t}$) of fuels i (naphta, diesel fuel, fuel oil) for period t obtained from the processing a certain amount of crude oil ($q_{P,t}$). The parameter $Fraction_i$ contains the fractional average coefficient relating both variables in an annual base. The values of $Fraction_i$ were estimated from reports from Argentina's Institute of Oil and Gas (Instituto Argentino de Petróleo y Gas (IAPG)) [21].

$$q_{i,t} = Fraction_i \cdot q_{P,t} \qquad \forall t; \quad \forall i \in Distillates \tag{5}$$

2.4. Demand and capacity constraints

Energy demands were estimated for each market k in period t (parameter $D_{k,t}$) and a linear growth was assumed for each period. Eq. (6) expresses the energy demand of market k in period t ($D_{k,t}$), which is calculated as the energy demand in the initial period ($D0_k$), plus the number of periods minus 1 times the increase average coefficient (α_k), which is an estimation based on the data gathered in previous years. Nevertheless different values can be proposed to α_k.

$$D_{k,t} = D0_k + \alpha_k \cdot (t-1) \qquad \forall t; \quad \forall k \tag{6}$$

Oil, gas and electricity demands for Argentina at the initial period (year 2010) were extracted from statistical data provided by Argentina's Energy Agency (Secretaria de Energía) [22]. The sectors consumption data were obtained from the Argentina's Statistics Agency (INDEC – Instituto Nacional de Estadísticas y Censos) [23] where they classify the energy consumptions by different uses (domestic, industrial, transportation, etc.). The statistical data for electric power is taken from the reports of the Argentina's Electricity Organizations (Mercado Eléctrico Mayorista (MEM) – Mercado Eléctrico Mayorista Sistema Patagónico (MEMSP)) of year 2010 [24]. These organization provides monthly reports on production and electricity demand, export and import of energy, consumption by pumping, projections for the sector and other information about the electricity sector. These reports discriminate also the source of the energy: fossils, hydropower, wind power, etc.

Eq. (7) states that the summation of the energy flows for a particular market k and period t must be greater than or equal to the demand for that destination in that period.

$$\sum_{i \in Markets_{i,k}} f_{i,k}\cdot x_{i,k,t}\cdot hr \geqslant D_{k,t} \qquad \forall t; \quad \forall k \tag{7}$$

In Eq. (7), $f_{i,k}$ is a parameter that relates the power source i to market k taking into account the performance and unit conversion factor needed between both. For example, the parameter $f_{GN,TN}$

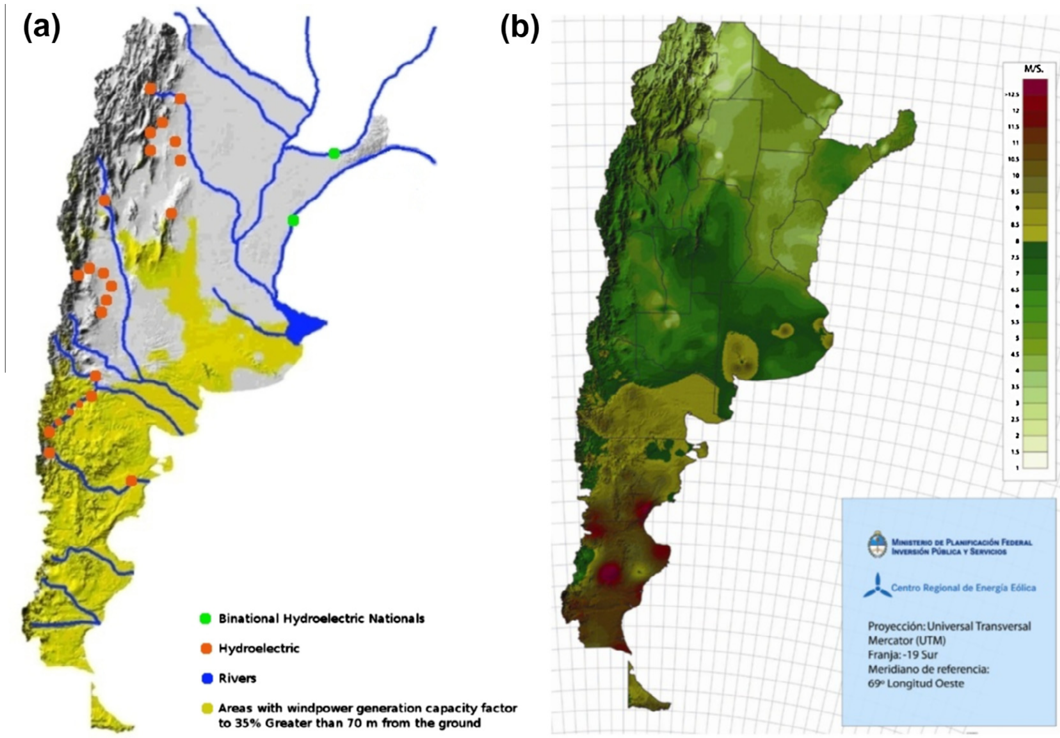

Fig. 3. Wind power and Hydropower capacity of installation [12]. (a): Map of rivers, dams and wind power capacity. (b): Map of mean annual wind speed at 50 m.

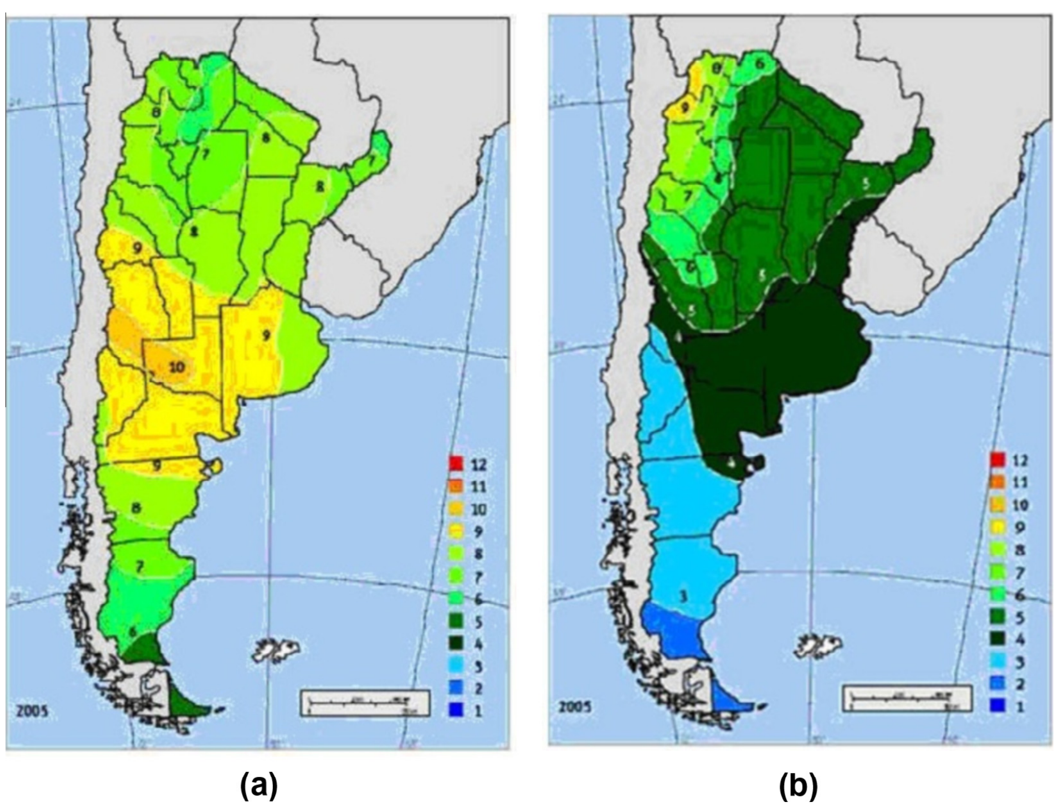

Fig. 4. Average solar radiation [12]. (a): January average radiation. (b): July average radiation.

relates natural gas as an energy source for the transportation market; its value is calculated as the ratio between the standard calorific power of the gas compared to gasoline, e.g., how many liters of gasoline would yield a m^3 of gas. For the case of the Uranium we estimate $f_{Nu,EE}$ based of the calorific power and efficiency of nuclear plants [31].

Table 1
Investments made from year 2000–2010 in energy for Argentina.

Source	Market	2000		2001		2004		2007		2007	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	0.77					59.44	0.77	59.44	0.77
Gas natural	Electric	4.25	0.01	4.25	0.01	4.25	0.01	4.25	0.01	4.25	0.01
Gas natural	Residential	622.18	183.7								
Bio diesel	Transport			144.34	135.94	20.43	18.92				
Wind power	Electric					889.64	99.51				

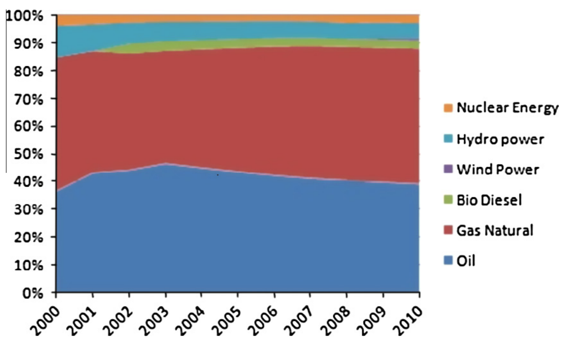

Fig. 5. Energy Matrix for Argentina from year 2000–2010.

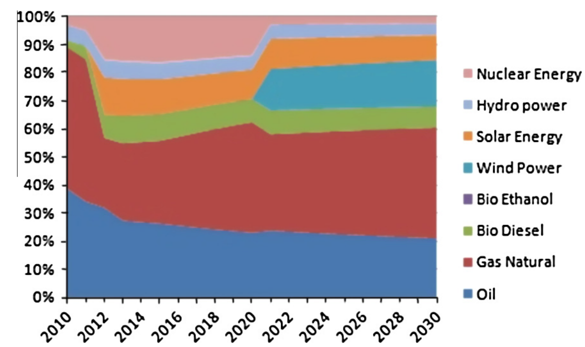

Fig. 6. Evolution of Energy Matrix of Scenario 1.

Eq. (8) states that energy production has a capacity limit represented by the variable $Cap_{i,k,t}$, this capacity varies from period to period according to the investment made. All sources have a maximum limit on the amount of energy that can be generated; this issue is explained in the next section.

$$f_{i,k} \cdot x_{i,k,t} \leqslant Cap_{i,k,t} \qquad \forall t; \quad \forall (i,k) \in Markets_{i,k} \tag{8}$$

2.5. Availability constraints

The equations of this section express the limit in energy provision for each source, for example, the amount produced by petroleum cannot exceed the volume of available reserves. In the case of renewables source the limitations are different. The installation of windmills is restricted by the free area available for them. For this case, we consider regions having airstreams blowing 80% of the time at operation ranges of wind turbines. For biomass sources, soybean crops for biodiesel and sugar cane for ethanol are taken into account, and the production is limited by the average amount of acreage, yield, and the annual harvest volume that goes to fuel production.

Eq. (9) states that production of energy source i in period t ($q_{i,t}$) is equal to the summation for all markets k of the energy flow ($x_{i,k,t}$) from source i in period t times the amount of annual operating hours. Eq. (10) states that the amount produced of source i must be less than or equal the available reserves for that source i in period t, represented by the variable $RD_{i,t}$.

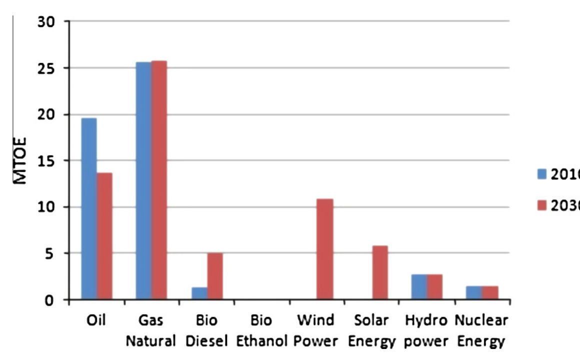

Fig. 7. TOE of the different source of Scenario 1.

$$q_{i,t} = \sum_{k \in Markets_{i,k}} x_{i,k,t} \cdot hr \qquad \forall t; \quad \forall i \tag{9}$$

$$q_{i,t} \leqslant RD_{i,t} \qquad \forall i \in NR \tag{10}$$

Eq. (11) restricts the ability to install renewable energy sources. The value of the parameter CD_i limits the new installation capacity, for example for the case of biodiesel from soybean, CD_{BD} corresponds to 1% of the total crop harvested multiplied by the average yield per acre times the estimated yield of biodiesel from this crop. These factors were taken according to the values suggested by Argentina's National Institute of Agriculture (Instituto Nacional de Tecnología

Table 2
Investments of Scenario 1.

Source	Market	2010		2011		2016		2024	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	0.37						
Biodiesel	Transport	144.34	135.95	144.34	135.08			68.74	20.89
Wind power	Electric					1779278.06	1234.51		
Solar energy	Residential	414.13	662.43						
Hydropower	Electric	18.14	1.37						

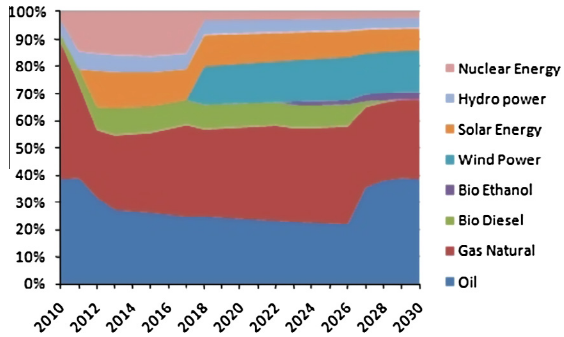

Fig. 8. Evolution of Energy Matrix of Scenario 2.

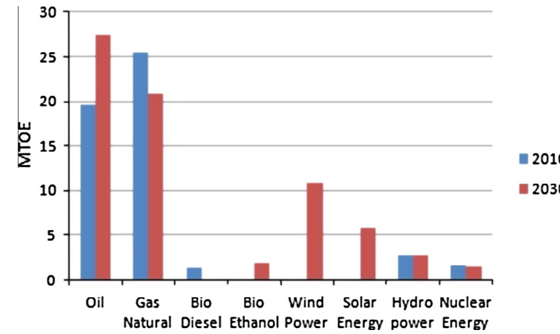

Fig. 9. TOE of the different source of Scenario 2.

Agropecuaria (INTA)) [25]. For bioethanol, a similar procedure was applied having sugarcane as raw material.

$$\sum_{k \in Markets_{i,k}} \frac{Cap_{i,k,t}}{f_{i,k}} \leqslant CD_i \qquad \forall t; \quad \forall i \notin NR \tag{11}$$

For windmills installation data were extracted from Argentina's Renewable Energy Association (Cámara de Energías Renovables de Argentina) [12], which presents a series of maps showing areas with suitable wind (see Fig. 3a and b). Fig. 3a shows in yellow the regions that would be suitable for windmills while Fig. 3b shows the annual average wind speed at 50 m above the ground level [12].

For solar energy we have a similar analysis. This paper only considers the application in residential and commercial heating. Therefore, if we take the spatial average value of daily global solar radiation, received on a horizontal surface (Fig. 4), it is possible to determine the feasible regions for the use of such energy. Furthermore, considering the population density and family type (4 members), we can estimate the number of possible facilities. Additionally, whit data from the Argentina's National Atomic Commission (Comisión Nacional de Energía Atómica) (File 1213-D-06) it is possible to calculate the volume of natural gas equivalent to the installation of solar heating.

Even when the technology is relatively new and it is not widely adopted yet, the use of hydro-kinetic turbines is considered for electricity generation due to the number of big rivers (Fig. 3a) with important constant values of water streams during the year. Analyzing the river flows, the geography of them and the power that a hydro-kinetic turbine can provide we have proposed a upper limit in the number of facilities and hence the electrical power supplied by this technology.

Eq. (12) indicates the reserves ($RD_{i,t=1}$) at the beginning of the time horizon. Eq. (13) evaluate the reserves available at period t, by considering the reserves in the previous period ($RD_{i,t-1}$) and the energy produced by source i in the period $t-1$ ($q_{i,t-1}$) plus the new reserves discovered in period t ($NewR_{i,t}$).

$$RD_{i,t=1} = \varepsilon_i \cdot CD_i \qquad \forall i \in NR \tag{12}$$

$$RD_{i,t} = RD_{i,t-1} - q_{i,t-1} + NewR_{i,t} \qquad \forall t > 1; \quad \forall i \in NR \tag{13}$$

2.6. Increase capacity constraints

Constraints (14) and (15) takes into account that there is a period of time from the moment you decide to invest in an energy source and when it starts producing, reflecting the time of the project construction and start-up. This time period is expressed by the parameter $T_{i,k}$, which is a factor depending on the energy source and its destination. The expression (14) indicates that the installed capacity of source i for market k at time t ($Cap_{i,k,t}$) is equal to the estimated initial capacity ($Cap0_{i,k}$); while Eq. (15) states that the installed capacity at time t greater than $T_{i,k}$ for source i and market k ($Cap_{i,k,t}$) is equal to the capacity at time $t-1$ ($Cap_{i,k,t-1}$) plus the increased capacity decided at time $t - T_{i,k}$ ($ICap_{i,k,t}$).

$$Cap_{i,k,t} = Cap0_{i,k} \qquad \forall t \leqslant T_{i,k}; \quad \forall (i,k) \in Markets_{i,k} \tag{14}$$

$$Cap_{i,k,t} = Cap_{i,k,t-1} + ICap_{i,k,t} \qquad \forall t > T_{i,k}; \quad \forall (i,k) \in Markets_{i,k} \tag{15}$$

2.7. Constraints for biofuels

Due to Argentina legislation and the operating conditions of engines, there are limits on the amount of biofuel that can be used, although exists engines that can use only this type of combustible, the Argentine vehicle fleet mostly works with motors that require fossil fuels to function properly. Considering this situation the biofuels produced in our country are blended with fossil until a certain amount; this is reflected by Eq. (16) for bioethanol, where we restrict the production relationship between gasoline and bioethanol by parameter BioNF (in our case $BioNF = 0,25$) and Eq. (17) for biodiesel.

$$q_{BE,t} \leqslant BioNF \cdot q_{Nf,t} \quad \forall t \tag{16}$$

$$q_{BD,t} \leqslant q_{GO,t} \quad \forall t \tag{17}$$

Table 3
Investments of Scenario 2.

Source	Market	2010		2011		2013		2021		2024	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	1.12								
Biodiesel	Transport	144.34	135.95	144.34	135.08					68.74	4.18
Bio etanol	Transport							484.69	175.16		
Wind power	Electric					1779278.06	1234.43				
Solar energy	Residential	414.13	662.43								
Hydropower	Electric	18.14	1.37								

Table 4
Investments of Scenario 3.

Source	Market	2010		2011		2024		2028	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	1.04						
Biodiesel	Transport	144.34	135.95	144.34	135.08	68.74	12.53		
Bio ethanol	Transport	384.68	81.53					384.68	93.63
Wind power	Electric			1779278.06	1234.44				
Solar energy	Residential	414.13	662.43						
Hydropower	Electric	18.14	1.37						

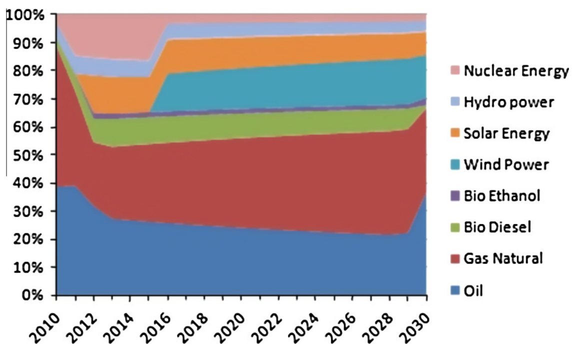

Fig. 10. Evolution of Energy Matrix of Scenario 3.

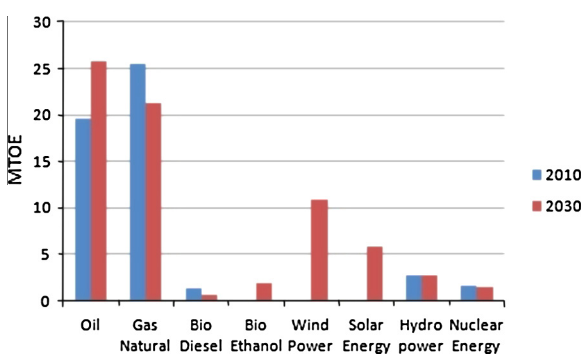

Fig. 11. TOE of the different source of Scenario 3.

Eq. (16) expresses that at most there will be a gasoline with 25% bioethanol, while (17) expresses an upper limit blend of 50% for biodiesel.

2.8. Calculation of depreciation

The calculation of depreciation is performed by assuming a straight-line method over the deductible amount. In the case of Argentina is considered that 85% of the total cost of the property divided by the years of lifetime of the good. Amortization is paid only during the useful life of the asset, but it is well known that the good financial life rarely matches the actual lifetime. This is the reason because we have considered extending the productive life along the horizon of the study but their rates are limited and estimated as posed in Eqs. (19) and (20).

In the absence of new investment the amortization cost ($Ca_{i,k,t}$) is zero as indicated in Eq. (18), when new plants start the production the depreciation is considered for those new investments ($CI_{i,k,t}$) until they complete their period of life, which is represented by the parameter $TVU_{i,k}$. After that period, no longer amortization is made as expressed by Eq. (20).

$$CA_{i,k,t} = 0 \qquad \forall t \leqslant T_{i,k}; \quad \forall (i,k) \in Markets_{i,k} \tag{18}$$

$$CA_{i,k,t} = CA_{i,k,t-1} + \frac{0.85 \cdot CI_{i,k,t-T_{i,k}}}{TVU_{i,k}} \qquad \forall t \leqslant TVU_{i,k} \quad \forall (i,k) \in Markets_{i,k} \tag{19}$$

$$CA_{i,k,t} = CA_{i,k,t-1} + \frac{0.85 \cdot \left(CI_{i,k,t-T_{i,k}} - CI_{i,k,t-T_{i,k}-TVU_{i,k}}\right)}{TVU_{i,k}} \quad \forall t > TVU_{i,k}, \quad \forall (i,k) \in Markets_{i,k} \tag{20}$$

2.9. Upper bound of investments

Eq. (21) expresses an upper limit in the amount of money to invests in a energy source i for a market k in a time period t through the parameter $Clup_{i,k,t}$.

$$CI_{i,k,t} \leqslant Clup_{i,k,t} \qquad \forall (i,k) \in Markets_{i,k} \quad \forall t \tag{21}$$

3. Results

With the aim of corroborating the behavior of the proposed model, we have selected data about consumptions, prices, markets, etc., from year 2000 to 2010 and analyze the results obtained with the real situation in Argentina in the Energy sector. In order to perform the analysis, some assumptions have been made to adjust the model to the policies and incentives in energy, as follows: (a) the use of solar energy and kinetic hydroturbines were neglected

Table 5
Investments of Scenario 4.

Source	Market	2010		2011		2014		2019		2021	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	0.37								
Biodiesel	Transport	144.34	135.95	137.47	93.3	114.56	62.67				
Wind power	Electric							1779278.06	1234.51		
Solar energy	Residential	414.13	662.43								
Hydropower	Electric									18.14	1.37

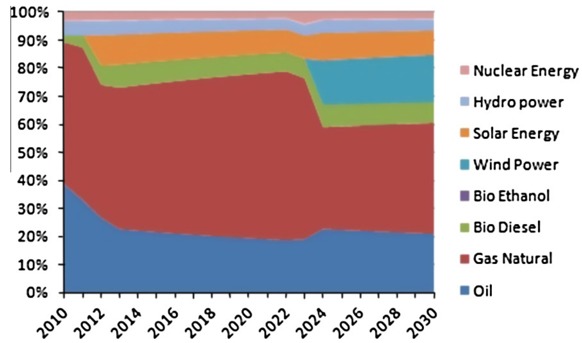

Fig. 12. Evolution of Energy Matrix of Scenario 4.

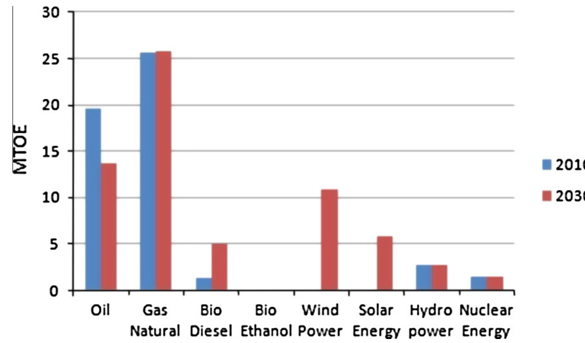

Fig. 15. TOE of the different source of Scenario 5.

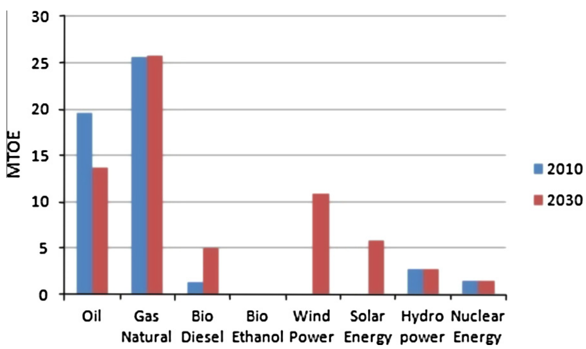

Fig. 13. TOE of the different source of Scenario 4.

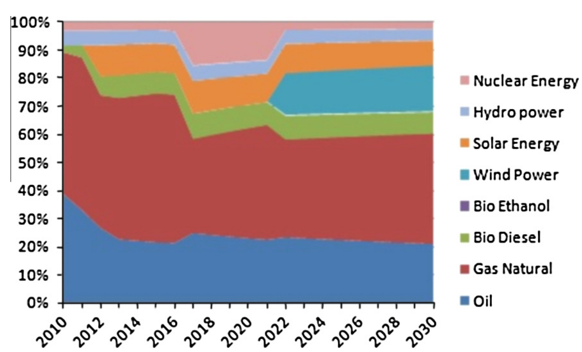

Fig. 14. Evolution of Energy Matrix of Scenario 5.

because there were not incentives at that time to use those technologies and (b) the money to invest in wind power was limited by an upper bound taking into account the subsidies provided by the national government in a special program called GENREN. During that period, there were great economic incentives and comparative advantages for private investments to produce biodiesel from soybean as feedstock, which was not the case for the production of bioethanol. With these premises we executed the model, and the results obtained are shown in Table 1 and Fig. 5.

From Table 1 it can be seen that there was investments in natural gas (NG) for commercial and residential heating (CR) increasing the consumption of this fuel; this was due to a gas duct connecting several populated cities started the operation at year 2000 and as a consequence, the consumption of natural gas for heating purposes increases around 35% from year 2003 [32]. Some power plants from natural gas were retrofitted in order to satisfy the increasing demand in electricity. For this market, several assets in fuel–oil (FO) was done for power plants to satisfy the demands in the electricity market (EE), which continuously grew in average 4% year starting at 2003 ([24]). During those years, private investors installed biodiesel plants from soybean as a raw material, which Argentina is the third world producer of this crop. The production of biodiesel grew from 260 thousands ton in year 2002 until 2000 thousands ton in 2009 [33]. Although the model predicted the amount to produce, the time to make the inversion was forecasted in advance. One explanation for this behavior is that in Argentina, after taking the investment decision, it is not rare to have a couple of years of delay to finish the project. From this table it can also be observed an asset for windpower due to a program subsidized by the government (GENREN Program [34]) for the installation of 200 MW h of wind energy, although the program was launched around 2006, the execution started in 2010, the model predicted the investment in year 2004 and the production in 2008; this situation can be corrected in the model imposing a constraint that limit the year where the asset must be made, the same can be done for the case of biodiesel. Analyzing the results obtained, we do believe that the model with proper adjustment can predict the investment and capacity needed for the energy sector with a good approximation.

The multiperiod disjunctive linear model was posed in GAMS [30] and solve with LogMIP. In this section we presents the results obtained solving several scenarios that contemplates different situations respect to the petroleum and gas reserves in Argentina. The scenarios proposed were based, essentially, in the discovery or not

Table 6
Investments of Scenario 5.

Source	Market	2010		2011		2014		2017		2024	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	0.37								
Biodiesel	Transport	144.34	135.95	144.34	135.08					68.74	20.89
Wind power	Electric							1779278.06	1234.51		
Solar energy	Residential	414.13	662.43								
Hydropower	Electric					18.14	1.37				

Table 7
Investments of Scenario 6.

Source	Market	2010		2011		2015/17/19		2021/23/25	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	0.37						
Biodiesel	Transport	144.34	135.95	137.47	97.1	114.56	8.73	114.56	8.35
Solar energy	Residential	414.13	662.43						

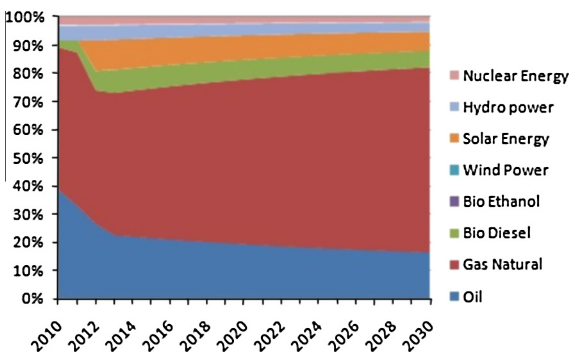

Fig. 16. Evolution of Energy Matrix of Scenario 6.

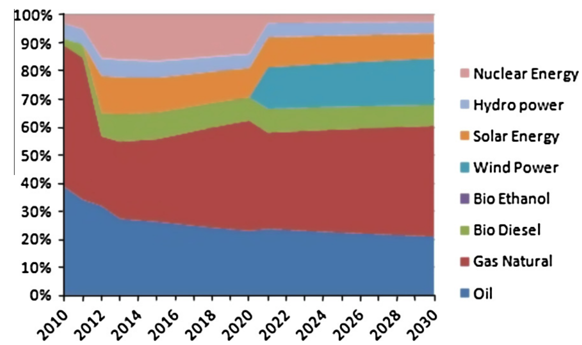

Fig. 18. Evolution of Energy Matrix of Scenario 7.

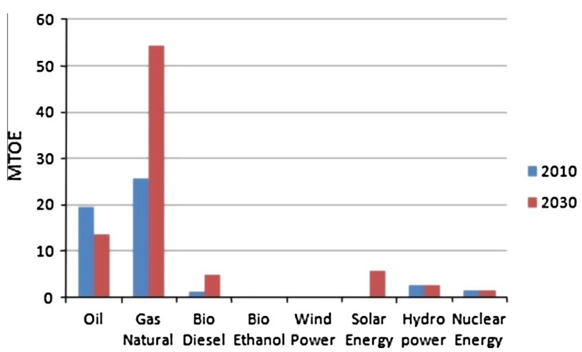

Fig. 17. TOE of the different source of Scenario 6.

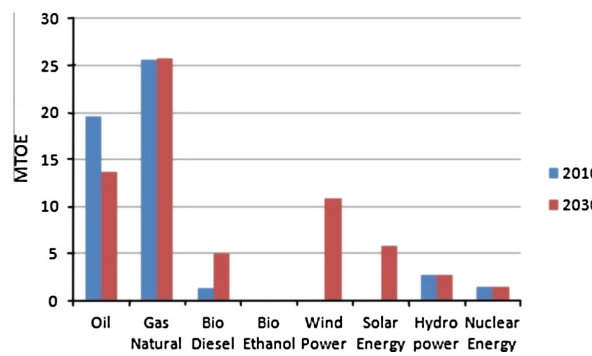

Fig. 19. TOE of the different source of Scenario 7.

of new fossils fuels reserves and its price variability. This was suggested based on the fact that for some decades Argentine?s energy matrix shall strongly depend on fossil fuels. Another important reason is the expectation on the technically recoverable shale oil and gas reserves from which Argentina is 4th in oil and 2nd in gas in the top ten ranking of the world. Due to these reasons the proposed scenarios were:

1. No new fossil fuels reserves are found and all available can be used in the time horizon. This scenario was proposed to include the worst case in terms of fossil fuels reserves and consumption.
2. No new fossil fuels reserves are found and a 10% of them must remain at the end of the time horizon. The idea behind this scenario was to analyze the investments behavior when not all the oil and gas available is allowed to be consumed in the time horizon.
3. No new fossil fuels reserves are found and a 10% of the gas and 20% of the oil must remain at the end of the time horizon. More gas reserves must remain at the end of 2030 because is the most important energy source in the matrix.
4. Natural gas reserves are increased 50% at year 2020. This scenario was proposed based on expectation in the production of shale gas reserves.

Table 8
Investments of Scenario 7.

Source	Market	2010		2011		2016		2024	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Fuel oil	Electric	59.44	0.37						
Biodiesel	Transport	144.34	135.95	144.34	135.08			68.74	20.89
Wind power	Electric					1779278.06	1234.51		
Solar energy	Residential	414.13	662.43						
Hydropower	Electric	18.14	1.37						

Table 9
Resume.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
NPV (MUS$)	54572.08	52154.22	51102.58	59740.92	57201.80	61953.10	54572.08
Total investment (MUS$)	1780127.19	1780611.88	1780896.55	1780166.14	1780127.19	1476.74	1780127.19
Capacity increased (TOE)	2190.60	2349.72	2358.00	2190.60	2190.60	954.78	2190.60

Table A.1
$Fraction_i$, Average percentage obtaining derivatives at the distill oil (m_i^3/m_P^3).

i	$Fraction_i$
NF	0.28
GO	0.37
FO	0.12

Table A.2
$T_{i,k}$, Execution time of civil works (years).

i	k				
	TN	TD	EE	CR	In
P					1
NF	1				1
GO		1			1
FO			2		1
GN	1		2	2	1
BD		2			1
BE	2				1
EO			5		1
SO				2	1
HC			2		1
NU			5		1

Table A.3
$TVU_{i,k}$, Useful Lifetime (years).

i	k				
	TN	TD	EE	CR	In
P					10
NF	10				10
GO		10			10
FO			10		10
GN	10		10	10	10
BD		10			10
BE	10				10
EO			15		10
SO				10	10
HC			10		10
NU			50		10

5. Natural gas reserves are increased 50% at year 2020, an increment of 200% in the natural gas cost and 30% of the reserves must remain. Since natural gas is the cheapest and most widely employed energy source, by proposing this situation the idea was to explore the behavior in the investments when NG price strongly increases.
6. Natural gas reserves are increased 100% at year 2020. Idem with scenario 4 with more NG available.
7. Oil reserves are increased 50% at year 2020. This scenario was proposed based on expectation in the production of shale oil reserves.

Other scenarios can be defined, these alternatives have been selected to demonstrate the capabilities of the proposed model.

Table A.4
$CapI0_{i,k}$, Initial production capacity.

i	k				
	TN (m³/h)	TD (m³/h)	EE (MW)	CR (m³/h)	In (m³/h)
P					11200.00
NF	3136.00				
GO		4144.00			
FO			0.46		1200000.00
GN	326018.37			102670.47	35514000000.00[a]
BD		315.49			
BE	38.09				
EO			80.00		
NU			10180.00		

[a] Including thermogenerators.

Table A.5
$D0_k$, Initial demand of k.

k (unit)	$D0_k$
TN (m_{NF}^3)	13482594.57
TD (m_{GO}^3)	9769182.91
EE (MW h)	71172765.00[a]
CR (m_{GN}^3)	8481395000.00

[a] Excluding the hydraulic generation (41169371 MW h).

Table A.6
$D_{k,t}$, Demand of k in period t.

t	k			
	TN (m_{NF}^3)	TD (m_{GO}^3)	EE (MW h)	CR (m_{GN}^3)
2010	13482594.57	9769182.91	71172765.00	8481395000.00
2011	14552126.56	9854163.00	74837582.21	8481733920.81
2012	15621658.55	9939143.09	78502399.42	8482072841.62
2013	16691190.54	10024123.18	82167216.63	8482411762.43
2014	17760722.53	10109103.27	85832033.84	8482750683.24
2015	18830254.52	10194083.36	89496851.05	8483089604.05
2016	19899786.51	10279063.45	93161668.26	8483428524.86
2017	20969318.50	10364043.54	96826485.47	8483767445.67
2018	22038850.49	10449023.63	100491302.68	8484106366.48
2019	23108382.48	10534003.72	104156119.89	8484445287.29
2020	24177914.47	10618983.81	107820937.10	8484784208.10
2021	25247446.46	10703963.90	111485754.31	8485123128.91
2022	26316978.45	10788943.99	115150571.52	8485462049.72
2023	27386510.44	10873924.08	118815388.73	8485800970.53
2024	28456042.43	10958904.17	122480205.94	8486139891.34
2025	29525574.42	11043884.26	126145023.15	8486478812.15
2026	30595106.41	11128864.35	129809840.36	8486817732.96
2027	31664638.40	11213844.44	133474657.57	8487156653.77
2028	32734170.39	11298824.53	137139474.78	8487495574.58
2029	33803702.38	11383804.62	140804291.99	8487834495.39
2030	34873234.37	11468784.71	144469109.20	8488173416.20

3.1. Scenario 1

Table 2 shows the results about the investment made for source i market k during the time horizon. Analyzing the results of this scenario, it is clear that fossil fuels reserves are not enough to cover

Table A.7
CD_i, Availability of i.

i (unit)	CD_i
P (m^3)	415914000.00
NF (m^3)	116455920.00
GO (m^3)	153888180.00
FO (m^3)	49909680.00
GN (m^3)	445100000000.00
BD (m^3/hr)	1108.85
BE (m^3/hr)	232.72
EO (MW)	9267073.20
SO (m^3_{GN})	712288.53
HC (MW)	16.00
NU ($kg_{uranium}$)	105000000.00

the energy demand in the time horizon analyzed, then investment are needed to expand the matrix to other sources. The investments are expressed in terms of thousands of US dollars and the increased capacities are shown in ton of oil equivalent (TOE). Major investments are made in wind power and biodiesel for the electrical and transportation sectors, respectively. The objective function value expressed in million of US dollars (MUS$) US$ 54572.08 and is based on economic terms and no environmental issues are included in this study. The total energy capacity was increased in (2190.6 TOE) and the investments correspond to a US$ 1780127.19.

Analyzing the evolution of the investments in Fig. 6, it can be seen that the first decisions are made at the beginning of the time period for hydro-kinetic turbines and solar calefaction, which start the production on 2012, reducing the needs of gas use for electricity and heating markets. In years 2010 and 2011 investments are made for two biodiesel plants starting their production in years 2012 and 2013, respectively decreasing the oil needed for the transportation sector. In 2021, electricity is produced by wind generators (decided in 2016), at this point a new drop in gas demand is produced. A new biodiesel plant starts its production in 2026 to decrease again the oil needed for the transportation sector. From Fig. 6, it can be seen that at the end of the period (2030) oil contribution is 21% compared to 39% at 2010, natural gas drops from 50% to 39%, biodiesel increases from 3% to 8%, no changes exists for bioethanol, wind energy increases from 0 to 17%, solar energy for calefaction goes from 0% to 9%, hydro power drops to 4% from 5%, and nuclear energy changes from 3% to 2%. Similarly, Fig. 7 illustrates the contribution of each energy source in terms of MTOE at the beginning (2010) and the end (2030) of the time horizon.

3.2. Scenario 2

Scenario 2 requires a residual value of 10% of the oil and gas reserves for year 2030. The objective function value is lower than scenario 1 (MUS$ 52154.22 NPV) while the new capacity installed (2349.72 TOE) and the investment performed (1780611.88 MUS$) are similar than scenario 1. Comparing the evolution curves for both scenarios, it can be seen that investments in hydro-kinetic turbines, solar energy and biodiesel plants are similar, and the main differences are: (a) the year when wind power mills are installed; in scenario 2 they start the production 3 years before (2018) than scenario 1 (2021) and (b) new bioethanol plant is installed in Scenario 2 for the transportation sector in order to reduce the use of oil. Installed nuclear power is also used for this scenario in similar manner than the previous case. According to Fig. 8, the matrix at year 2030 is composed of: oil 39%, natural gas 29%, 0% biodiesel, 3% bioethanol, wind energy 15%, solar energy for heating 8%, hydro power 4%, and nuclear energy 2%. The use of oil is reduced at beginning of the period, then moderately employed until year 2027 and after its use is increased. The explanation for this behavior is that oil prices raise improving the revenues. (see Table 3 and Fig. 9).

3.3. Scenario 3

In this scenario, there is a requirement that a residual value of 10% of the gas and 20% of the oil reserves must remain at the end of the time horizon. The results obtained shows an increment in the investment (MUS$ 1780896.55) and capacity installed (2358 TOE) on renewable sources with a lower objective function value (NPV) MUS$ 51102.58. An important difference between this scenario and the previous are that investments for windmills and bioethanol plants are made in advanced. Two ethanol plants are installed in this case and the total production for this biofuel at

Table A.8
$CO_{i,k,t}$, Operative cost of TN, TD and CR.

t	k						
	TN			TD		CR	
	i						
	NF (\$/m^3)	GN (\$/m^3)	BE (\$/m^3)	GO (\$/m^3)	BD (\$/m^3)	GN (\$/m^3)	SO (\$/m^3_{GN})
2010	100.00	28.00	1.00	10.00	7.00	1.01	0.06
2011	114.61	34.36	1.21	12.27	9.87	1.24	0.07
2012	131.95	42.14	1.49	15.21	10.15	1.52	0.09
2013	152.53	51.60	1.85	19.01	10.31	1.86	0.11
2014	176.94	63.10	2.32	23.93	10.43	2.28	0.13
2015	205.92	77.11	2.95	30.30	10.52	2.78	0.16
2016	240.30	94.18	3.77	38.55	10.60	3.40	0.20
2017	281.11	114.95	4.84	49.24	10.65	4.15	0.24
2018	329.53	140.25	6.26	63.06	10.71	5.06	0.29
2019	386.99	171.05	8.11	80.97	10.75	6.17	0.36
2020	455.19	208.56	10.55	104.14	10.80	7.52	0.44
2021	536.12	254.23	13.76	134.15	10.83	9.17	0.53
2022	632.15	309.84	17.96	173.00	10.87	11.18	0.65
2023	746.11	377.55	23.49	223.30	10.90	13.62	0.79
2024	881.35	459.99	30.75	288.41	10.93	16.59	0.96
2025	1041.84	560.38	40.28	372.71	10.96	20.21	1.17
2026	1232.30	682.61	52.81	481.84	10.98	24.62	1.42
2027	1458.30	831.45	69.26	623.13	11.01	29.99	1.73
2028	1726.50	1012.67	90.86	806.05	11.03	36.53	2.11
2029	2044.78	1233.33	119.24	1042.86	11.05	44.49	2.57
2030	2422.48	1502.02	156.51	1349.45	11.07	54.18	3.13

Table A.9
$CO_{i,k,t}$, Operative cost of EE and In.

t	k							
	EE					In		
	i							
	FO ($/MW h)	GN ($/MW h)	EO ($/MW h)	HC ($/MW h)	NU ($/MW h)	P ($/m^3)	FO ($/m^3)	GN ($/m^3)
2010	0.01	0.01	40.50	0.02	50.00	2167.17	3914.14	1594.86
2011	0.01	0.01	49.34	0.02	60.94	2423.77	4529.34	1957.99
2012	0.01	0.01	59.93	0.03	73.99	2705.01	5218.44	2400.14
2013	0.01	0.01	72.55	0.04	89.57	3013.25	5990.30	2938.52
2014	0.01	0.01	87.61	0.04	108.16	3351.10	6854.88	3594.06
2015	0.01	0.01	105.59	0.05	130.35	3721.38	7823.29	4392.26
2016	0.01	0.01	127.04	0.06	156.84	4127.22	8908.01	5364.16
2017	0.02	0.02	152.64	0.08	188.44	4572.03	10123.02	6547.58
2018	0.02	0.02	183.20	0.09	226.17	5059.56	11483.96	7988.54
2019	0.02	0.02	219.67	0.11	271.19	5593.90	13008.35	9743.08
2020	0.03	0.03	263.20	0.13	324.93	6179.54	14715.84	11879.45
2021	0.03	0.03	315.14	0.16	389.06	6821.43	16628.40	14480.75
2022	0.04	0.04	377.13	0.19	465.60	7524.95	18770.69	17648.15
2023	0.05	0.05	451.13	0.22	556.95	8296.03	21170.27	21504.86
2024	0.06	0.06	539.44	0.27	665.97	9141.16	23858.06	26200.87
2025	0.07	0.07	644.84	0.32	796.09	10067.43	26868.67	31918.86
2026	0.08	0.09	770.63	0.38	951.39	11082.65	30240.88	38881.21
2027	0.10	0.09	920.77	0.46	136.74	12195.36	34018.11	47358.73
2028	0.10	0.11	1099.93	0.54	1357.94	13414.91	38249.01	57681.17
2029	0.12	0.13	1313.78	0.65	1621.95	14751.58	42988.08	70250.01
2030	0.16	0.16	1569.00	0.78	1937.04	16216.59	48296.34	85554.14

Table A.10
$P_{i,k,t}$, Sale price of TN, TD and CR.

t	k						
	TN			TD		CR	
	i						
	NF ($/m^3)	GN ($/m^3)	BE ($/m^3)	GO ($/m^3)	BD ($/m^3)	GN ($/m^3)	SO ($/m$^3_{GN}$)
2010	1383.49	1063.24	2803.14	1.80	3216.03	1063.24	1063.24
2011	1585.63	1305.33	3390.75	2.20	4535.85	1305.33	1305.33
2012	1825.51	1600.10	4162.55	2.72	4663.46	1600.10	1600.10
2013	2110.17	1959.01	5176.28	3.40	4738.12	1959.01	1959.01
2014	2447.98	2396.04	6507.79	4.28	4791.10	2396.04	2396.04
2015	2848.86	2928.17	8256.68	5.42	4832.20	2928.17	2928.17
2016	3324.58	3576.11	10553.79	6.90	4865.78	3576.11	3576.11
2017	3889.12	4365.05	13570.96	8.81	4894.17	4365.05	4365.05
2018	4559.06	5325.69	17533.93	11.29	4918.76	5325.69	5325.69
2019	5354.08	6495.39	22739.15	14.49	4940.45	6495.39	6495.39
2020	6297.52	7919.63	29576.05	18.64	4959.86	7919.63	7919.63
2021	7417.10	9653.83	38556.09	24.01	4977.42	9653.83	9653.83
2022	8745.71	11765.43	50351.07	30.96	4993.44	11765.43	11765.43
2023	10322.37	14336.57	65843.40	39.96	5008.19	14336.57	14336.57
2024	12193.39	17467.25	86192.07	51.61	5021.84	17467.25	17467.25
2025	14413.73	21279.24	112919.38	66.69	5034.54	21279.24	21279.24
2026	17048.61	25920.80	148024.84	86.22	5046.43	25920.80	25920.80
2027	20175.41	31572.49	194134.71	111.50	5057.60	31572.49	31572.49
2028	23885.98	38454.11	254698.52	144.24	5068.13	38454.11	38454.11
2029	28289.32	46833.34	334247.11	186.61	5078.08	46833.34	46833.34
2030	33514.75	57036.09	438731.58	241.47	5087.53	57036.09	57036.09

the end of the period is higher than scenario 2. An explanation is that for this case the residual reserves in oil must remain higher than the previous scenario. The energy matrix for this case for the year 2030 is composed of: oil 37%, natural gas 30%, biodiesel 1%, bioethanol 3%, wind power 15%, solar energy for calefaction 8%, hydro power 4%, and nuclear energy 2% (see Table 4, Figs. 10 and 11).

3.4. Scenario 4

Scenario 4 contemplates that natural gas reserves increase 50% at year 2020. This situation has an important impact in the revenues, since the objective function is higher than the previous 3 scenarios, having a value of 59740.92 MUS$, investments remains similar than the previous (1780166.14 MUS$) and the new capacity installed is of 2190.6 TOE. Due to more availability of natural gas, which is the cheapest source to produce electricity, its use is extended in the whole time horizon, that is the reason for delaying the investments in wind electricity generators until year 2019 and hydro-kinetic turbines until 2021. Note that in previous scenarios it was selected in earlier years. bioethanol is not used for gasoline since it can be replaced by gas for the transportation market. In contrast, biodiesel is used for heavy transports. Energy matrix composition for this scenario at year 2030 is: 21% oil, 39% natural gas, 8% biodiesel, 0% bioethanol, 17% wind power, 9% solar, 4% hydro power and 2% nuclear energy (see Table 5 and Figs. 12 and 13).

Table A.11
$P_{i,k,t}$, Sale price of EE and In.

t	k							
	EE					In		
	i							
	FO (\$/MW h)	GN (\$/MW h)	EO (\$/MW h)	HC (\$/MW h)	NU (\$/MW h)	P (\$/m^3)	FO (\$/m^3)	GN (\$/m^3)
2010	209.64	209.64	209.64	209.64	209.64	1444.78	2609.42	1063.24
2011	255.50	255.49	255.49	255.49	255.49	1615.85	3019.56	1305.33
2012	310.22	310.22	310.22	310.22	310.22	1803.34	3478.96	1600.10
2013	375.54	375.54	375.54	375.54	375.54	2008.84	3993.54	1959.01
2014	453.49	453.49	453.49	453.49	453.49	2234.06	4569.92	2396.04
2015	546.53	546.53	546.53	546.53	546.53	2480.92	5215.53	2928.17
2016	657.57	657.57	657.57	657.57	657.57	2751.48	5938.67	3576.11
2017	790.10	790.10	790.10	790.10	790.10	3048.02	6748.70	4365.05
2018	948.26	948.26	948.26	948.26	948.26	3373.04	7655.97	5325.69
2019	1137.03	1137.03	1137.03	1137.03	1137.03	3729.26	8672.23	6495.39
2020	1362.33	1362.33	1362.33	1362.33	1362.33	4119.70	9810.56	7919.63
2021	1631.22	1631.22	1631.22	1631.22	1631.22	4547.62	11085.60	9653.83
2022	1952.13	1952.13	1952.13	1952.13	1952.13	5016.64	12513.79	11765.43
2023	2335.14	2335.14	2335.14	2335.14	2335.14	5530.69	14113.51	14336.57
2024	2792.25	2792.25	2792.25	2792.23	2792.25	6094.10	15905.37	17467.25
2025	3337.81	3337.81	3337.81	3337.81	3337.81	6711.62	17912.45	21279.24
2026	3988.93	3988.93	3988.93	3988.93	3988.93	7388.43	20160.58	25920.80
2027	4766.03	4766.03	4766.03	4766.03	4766.03	8130.24	22678.74	31572.49
2028	5693.49	5693.49	5693.49	5693.49	5693.49	8943.28	25499.34	38454.11
2029	6800.40	6800.40	6800.40	6800.40	6800.40	9834.38	28658.72	46833.34
2030	8121.49	8121.49	8121.49	8121.49	8121.49	10811.06	32197.56	57036.09

Table A.12
$Imax_{r,i,k,t}$, Discretization of new installation capacity.

i	k	r				
		1	2	3	4	Unit
P	In	1060.51	2121.03	3181.54	4454.15	m^3/h
NF	TN	296.94	593.89	890.83	1247.16	m^3/h
GO	TD	392.39	784.78	1177.17	1648.04	m^3/h
FO	EE	114.86	229.73	344.59	482.43	MW
FO	In	127.26	254.52	381.78	534.50	m^3/h
GN	TN	81504.59	163009.19	244513.78	342319.29	m^3/h
GN	EE	3.59	7.18	10.77	15.08	MW
GN	CR	256675.12	513350.23	770025.35	1078035.49	m^3/h
GN	In	44219.28	88438.55	132657.83	185720.96	m^3/h
BD	TD	37.55	75.11	112.66	157.73	m^3/h
BE	TN	61.18	122.36	183.54	256.96	m^3/h
EO	EE	2316768.30	4633536.60	6950304.90	9730426.86	MW
SO	CR	178072.50	356145.00	534217.50	747904.50	m$^3_{GN}$/h
HC	EE	4.00	8.00	12.00	16.80	MW
NU	EE	10.18	20.36	30.54	42.76	MW

3.5. Scenario 5

Scenario 5 includes an increment of natural gas reserves of 50% at year 2020, the production cost is raised 200% and requires that at the end of the time period 30% of the total reserves must remain. The idea behind this approach was to analyze the effect of an increased cost of gas. In this sense, comparing this case against scenario 4, it can be observed from Fig. 14 the use of nuclear installed capacity for electricity from year 2016 because is now competitive, investments in wind and hydro-kinetic power are made two years in advance for the same reason. The conclusion is that even with a high increase in the cost of gas, and the needs to maintain reserves at the end of the period; gas is used as the main source for producing electricity. This scenario have an NPV value of 57201.8 MUS\$, with investments of 1780127.19 MUS\$ and the new capacity installed is 2190.6 TOE. Energy matrix composition for this scenario at year 2030 is: 21% oil, 39% natural gas, 8% biodiesel, 0% bioethanol, 17% wind power, 9% solar, 4% hydro power and 2% nuclear energy (see Table 6 and Fig. 15).

3.6. Scenario 6

For this case gas reserves are increased 100% at year 2020. In this case due to the excess in gas and its convenient price, it is used for every market (electricity, transportation, heating) in the whole time horizon. No investments are made in wind power for electricity. Since oil reserves remain constant, new biodiesel plants are installed in order to satisfy the transport market. Highest revenues are obtained in this Scenario (61953.1 MUS\$), investments drops to 1476.74 MUS\$ and the new capacity installed is about 954.78 TOE. At the end of the period, the energy matrix is composed by 16% oil, 66% gas, biodiesel 6%, solar energy 7%, nuclear energy 2% and 3% hydro power (see Table 7 and Figs. 16 and 17).

3.7. Scenario 7

For this case oil reserves are increased 50% at year 2020. Revenues (54572.08 MUS\$), investments (1780127.19 MUS\$) and new capacities (2190.6 TOE) are similar than the first 3 scenarios. The conclusion is that having more oil reserves does not make a big difference than having more natural gas reserves concluding that oil price and operating cost are not as convenient than natural gas. On the other hand, petroleum is almost irreplaceable for the heavy transport, only biodiesel can be used for this market but its production is limited. Results obtained for this scenario are same than those for scenario 1. At the end of the 2030 period, the energy matrix is composed by 21% oil, 39% gas, biodiesel 8%, 17% wind power, solar energy 9%, nuclear energy 2% and 4% hydro power. This values are same than scenario 1, where oil reserves are used over the total period (see Table 8 and Figs. 18 and 19).

Table 9 present a summary of the objective function, total investment and total capacity increased on each of the scenario described. From this table it can be seen that investments are dominated by winds generators farms comparing with the assets in other sources. The objective function grows directly proportional to the availability of natural gas even when the price and operating cost is increased. On the other hand, the excess of oil does not have a great impact in the revenues and the energy matrix composition. The total installed capacity measures in TOE grows when reserves

Table A.13
$Cm_{r,i,k,t}$, Discretization of new installation costs.

i	k	r				
		1	2	3	4	Unit
P	In	6363078.00	10605130.00	12726156.00	13362463.80	$\$/m^3/h$
NF	TN	712664.40	1187774.00	1425328.80	1496595.24	$\$/m^3/h$
GO	TD	706301.55	1177169.25	1412603.10	1483233.26	$\$/m^3/h$
FO	EE	297178.73	495297.88	594357.46	624075.33	$/MW
FO	In	152.71	254.52	305.43	320.63	$\$/m^3/h$
GN	TN	97805511.30	163009185.50	195611022.60	205391573.73	$\$/m^3/h$
GN	EE	10113.78	16856.29	20227.55	21238.93	$/MW
GN	CR	3110902.42	5184837.36	6221804.84	6532895.08	$\$/m^3_{GN}/h$
GN	In	53063.13	88438.55	106126.26	111432.57	$\$/m^3/h$
BD	TD	343675.75	572792.91	687351.49	721719.07	$\$/m^3/h$
BE	TN	1154032.08	1923386.80	2308064.16	2423467.37	$\$/m^3/h$
EO	EE	8896390272.00	14827317120.00	17792780544.00	18682419571.20	$/MW
SO	CR	986022.34	1643370.56	1972044.67	2070646.90	$\$/m^3_{GN}/h$
HC	EE	43200.00	72000.00	86400.00	90720.00	$/MW
NU	EE	129782784.00	216304640.00	259565568.00	272543846.40	$/MW

Table A.14
$f_{i,k}$, Conversion factor and performance.

i	k	$f_{i,k}$	Unit
P	In	1	–
NF	TN	1	–
GO	TD	1	–
FO	EE	0.004	$kW\ h/m^3$
FO	In	1	–
GN	TN	0.001	m^3_{NF}/m^3_{GN}
GN	EE	0.004	$kW\ h/m^3$
GN	CR	1	–
GN	In	1	–
BD	TD	1	–
BE	TN	1	–
EO	EE	1	–
SO	CR	1	–
HC	EE	1	–
NU	EE	44106.306	kW h/kg

of oil remain constant and stays in the same value when new reserves are discovered.

4. Conclusions

In this work, a mathematical optimization model for investment planning in energy for Argentina is presented. The objective function is the maximization of the Net Present Value (NPV) in the time horizon of 20 years (2010–2030). Revenues, operation, startup, and amortization costs of new energy facilities are considered in the model. Based on the fact that for the next decades energy will not depend just on fossil fuels, in this work investments on renewable and non-renewable sources are included. Limits in both resources are taken into account in order to achieve a realistic representation. Renewable energy sources having advantages for Argentina are included in the model: wind generators, soybean biodiesel, bioethanol from sugarcane, hydro-kinetic turbines and solar energy for residential and commercial heating.

Several examples were solved in order to exhibit the capabilities of the model. Scenarios posed different situations to analyze the model responses. Solutions showed how the different elements interact to achieve an effective and efficient operation of the global energy system. Precisely, the simultaneous analysis of all elements involved is the great advantage of the application of mathematical programming to this context.

The model allows the analysis and evaluation of different scenarios helping the decision making on economical energy alternatives to invest in order to satisfy actual and future demands. Results show that investments in renewable sources are made because of limits in non-renewable supplies. When there are enough reserves like the case of scenario 6 for natural gas, it is employed as main source in the whole scenario. Nevertheless, results obviously depend on the parameters adopted, in a sensitive area, where prices and costs are affected by political, environmental and some other factors. This is another advantage of this tool, where the impact of changes can be quickly considered.

Although the model has been posed for the Argentinean case, the methodology can easily extend to consider other cases and scenarios. In effect, a great advantage of the proposed formulation is its application to different contexts considering the simultaneous representation of the different aspects.

Future work will include in the model other considerations besides the economic aspects like greenhouse gas emissions and/or energy source lifecycle.

5. Nomenclature

5.1. Sets

i	Source of energy
	P – crude oil
	Nf – Naphtha
	GO – diesel oil
	FO – fuel oil
	GN – natural gas
	BD – biodiesel
	BE – bioethanol
	Eo – wind power
	So – solar energy
	HC – hydropower
	Nu – nuclear energy
k	Market
	TN – transport: gasoline engines
	TD – transport: diesel engines
	EE – electric energy
	CR – residential demand
	In – industrial demand
t	periods of time

r	capacity range
$Distillates_i$	secondary sources obtained from the processing of oil (*Nf, GO, FO*)
$Markets_{i,k}$	relationship between source i and the market k

5.2. Paramaters

NT	nominal tax rate
TI	interest rate
hr	operating hours
$BioNF$	relationship between gasoline and bioethanol blend
$Fraction_i$	average percentage obtaining derivatives at the distill oil
$T_{i,k}$	execution time of civil works
$TUV_{i,k}$	useful lifetime
$Cap0_{i,k}$	initial productivity capacity
$D0_k$	initial demand of k
$D_{k,t}$	demand of k in period t
CD_i	availability of i
$CO_{i,k,t}$	operative cost
$P_{i,k,t}$	sale price
$CS_{i,k,t}$	start up cost
$Cm_{r,i,k,t}$	discretization of new installation costs
$Imax_{r,i,k,t}$	discretization of new installation capacity
$f_{i,k}$	conversion factor and performance
$NewR_{i,t}$	new reserves
$CIup_{i,k,t}$	upper bound for the cost of the new installations

5.3. Variables

$CSF_{i,k,t}$	cash flow
$CA_{i,k,t}$	depreciation
$x_{i,k,t}$	flow of i, destinated to k in the period t
$CI_{i,k,t}$	cost of the new installations
$ICap_{i,k,t}$	capacity of the new installations
$w_{i,k,t}$	decision variable for a new installations
$y_{r,i,k,t}$	decision variables for a capacity range
$q_{i,t}$	production of the source i, in the period t
$Cap_{i,k,t}$	capacity in period t
$RD_{i,t}$	reserves of the non-renewable source i, in the period t

Appendix A. Data for model execution

$NT = 0.08$, Nominal tax rate.
$TI = 0.30$, Interest rate.
$hr = 8765.81$, Operating hours.
$BioNF = 0.25$, Relationship between Gasoline and Bioethanol blend.

Tables A.1–A.14.

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