Computers and Chemical Engineering 72 (2015) 222–232

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Investment planning in energy considering economic and environmental objectives

Julio Flores, Jorge M. Montagna, Aldo Vecchietti*

INGAR – Instituto de Desarrollo y Diseño (CONICET-UTN), Avellaneda 3657, Santa Fe 3000, Argentina

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 1 May 2014
Accepted 3 May 2014
Available online 13 May 2014

Keywords:
Renewable energy
Investment planning
Multi-objective multiperiod optimization
Environmental and Economic impact

ABSTRACT

This work proposes a linear disjunctive multiperiod optimization model for planning investments in energy sources considering two objectives, one economical (maximization of the net present value), and the other environmental (minimization of greenhouse gas emissions – GHG). The general goal of this approach is to provide an analysis tool for energy decision makers in planning investment considering different scenarios in GHG emanation. The decision variables of the model are the investment needs in money, capacity and time in order to satisfy 100% of the energy market for Argentina in the period 2010–2030. Two models are proposed, the first one considers the total amount of GHG released in the horizon time; and the other contemplates the amount of GHG year by year. Twenty scenarios are evaluated with both models. The results obtained are presented, which show the trade-offs between both objectives.

1. Introduction

Every country in the near future must face the energy supply using sustainable sources to maintain the population quality of life (IEA, 2012). This situation has emerged, among others, due to the limited amount of fossil fuel reserves and the global warming effect of the greenhouse gas (GHG) emissions. In the decades to come, central governments have the challenge of delivering energy in an economically and environmental friendly way. Several renewable and sustainable energy sources such as wind power, solar, biofuels, have a certain level of maturity and they are producing an important amount of energy around the world (IEA, 2013; IPCC, 2011; Wüstenhagen and Menichetti, 2012). All of them have the advantage of neutral or zero GHG emissions but they cannot compete economically and/or in some other features like availability, power, etc., compared with petroleum or natural gas. The Energy Departments must visualize an investment plan in energy via economic incentives and subsidies considering comparative advantages in natural resources. This work proposes a multiperiod optimization model for planning investments in energy considering two objectives, one economical, the maximization of the net present value (NPV), and the other environmental, the minimization of GHG emissions. The general goal of this approach is to provide an analysis tool for decision makers where different future scenarios can be evaluated in order to provide information about the more suitable energy sources to invest considering the opposite objectives pursued.

In the literature there are several works related to those subjects, Cicea et al. (2014) present an article to evaluate the environmental efficiency of investments in renewable energy. They propose a method considering econometric models based on Kaya identity, which is an equation used in studies regarding emissions. They use indicators like energy intensity, CO_2 intensity and gross domestic product per capita and per unit of investment; with this data they proposed the calculation of an environmental efficiency index; which they claim is the novelty of their work. The proposed index is applied to several countries in the European Union. Careri et al. (2011) presented a Generation Expansion Planning (GEP) problem to find the optimal strategy to plan the construction of new generation plants while satisfying technical and economical constraints. With this model it is possible to analyze the impact of some of the most popular incentive systems (namely feed-in tariffs, quota obligation, emission trade, and carbon tax) on generation planning. The resulting problem is solved using generalized Benders decomposition (GBD) approach, implemented in Matlab programming language. They included in the article some tests related with the Italian system. Tang et al. (2012) introduced and formulated a carbon revenue bond as a financing tool to support investments in renewable energy, which complements other environmental incentives. According to these authors,

* Corresponding author. Tel.: +54 3424534451.
E-mail addresses: jflores@santafe-conicet.gov.ar (J. Flores), jmmontagna@santafe-conicet.gov.ar (J.M. Montagna), aldovec@santafe-conicet.gov.ar (A. Vecchietti).

http://dx.doi.org/10.1016/j.compchemeng.2014.05.006
0098-1354/

Nomenclature:

Sets:

i	set for source of energy
k	set for markets
t	periods of time
r	capacities intervals
$Markets_{i,k}$	subset that indicates that source i can supply market k
NR	subset of nonrenewable energy sources

Parameters:

NT	Tax rate
TI	interest rate
hr	annual operating hours
$P_{i,k,t}$	selling price of energy sources i, for the market k, in the period t
$CO_{i,k,t}$	operating cost of energy sources i, for the market k, in the period t
$T_{i,k}$	construction time
α_{Dep}	depreciation percentage
$TVU_{i,k}$	useful life time
ε	epsilon parameter
$GGEI^{up}_{k,t}$	Emissions taken as upper bound to each market k and in each period t
$fGEI_{i,k}$	emission factor for each source i and market k
$x^{Sol}_{i,k,t}$	optimal solution taken as upper bound
$D_{k,t}$	estimated demand
$D0_k$	initial demand
α_k	factor increasing demand
$Cm_{r,i,k}$	scaling parameter of the investment cost
$Imax_{r,i,k}$	scaling parameter for capacity of converse plants
$CSm_{r,i,k}$	scaling parameter for the start-up cost of new plants
$Cap0_{i,k}$	initially installed capacities for sources i, market k
$RD0_i$	nonrenewable reserves available at the beginning of the horizon time for source i
$f_{i,k}$	performance conversion factor of source i into the form required for market k
CD_i	availability of renewable resources

Variables:

NPV	net present value
$CSF_{i,k,t}$	cash flows for each source i, market k and period t
$CA_{i,k,t}$	amortization cost
$x_{i,k,t}$	hourly energy flow from source i to market k in period t
$CI_{i,k,t}$	investment cost
$CS_{i,k,t}$	start-up cost
$XGEI_{k,t}$	emissions of greenhouse gases in tons of CO_2
$Cap_{i,k,t}$	capacity available from the source i to market k in period t
$w_{i,k,t-T_{i,k}}$	binary decision variable of existence of investments
$y_{r,i,k,t-T_{i,k}}$	binary decision variable of level of investments
$ICap_{i,k,t}$	increased capacity for new investments
$RD_{i,t}$	nonrenewable reserves available at time t for source i

renewable energy systems depend on large financial incentives to compete with conventional generation methods. The value of the bond is obtained by predicting future revenues using stochastic and historical price data. They applied the methodology to three different markets: Europe, Australia and New Jersey. They conclude that the sale of the carbon revenue bond with a ten year maturity can finance a significant portion of a project's initial cost. Fazlollahi et al. (2012) worked on methods for multi-objective investment and operating optimization of complex energy systems. The idea behind the article is to explore a multi-period energy system optimization (ESO) model with a mono objective function and compare it with a multi-objective optimization perspective to systematically generate a good set of solutions by using integer cut constraints (ICC) algorithm and ε constraint. They applied the proposed model to several case studies comprising six types of conversion technologies, namely, a heat pump, boiler, photovoltaics, as well as a gas turbine, fuel cell and gas engine. The authors conclude that the model is particularly suited for multi-objective optimizations presenting different trade-offs among them. Giarola et al. (2011) propose a multi-objective Mixed Integer Linear Programming (MILP) framework to optimize the environmental and financial performances of corn grain- and stover-based bioethanol supply chains. The first objective is the maximization of profit and the second one is to minimize the total GHG impact resulting from the operation of the biofuel SC over a 15-year time horizon. The model was applied to a real world case study: the emerging bioethanol infrastructure in Northern Italy. A Pareto set of sub-optimal solutions is obtained from the bi-objective problem solution, the results reveals the conflict between environmental and economic performance in dealing with biofuels productions. The authors claim the effectiveness of the optimization tool at providing decision makers with a quantitative analysis assessing the economic and environmental performances of different design configuration and their effect in terms of technologies, plant sizes and location, and raw materials. An extension of this work is presented by Bernardi et al. (2012, 2013) who formulate a multiobjective MILP modeling framework to optimize the environmental (carbon and water footprints) and economic performances of bioethanol supply chains. They include the water consumption as an objective to minimize, due scarcity of this resource in some regions and the evidence that large-scale biofuels production can affect the overall water footprint significantly. They also applied the model to the same case study (corn and stover bioethanol, north of Italy). In the article of 2012 the authors conclude that some ethanol production processes (first-generation) involve intensive use of water resources and the results are significantly affected by the procedure used to account for by-product end-use effect on the overall environmental supply chain performance. While in the work published in 2013, they assert that the novelty is the contribution assessment compared to the previous one, because the amount of water consumed for cropping has a geographical dependency and it is estimated according to a spatially explicit approach.

One key sector that needs more insight is the transportation segment which strongly depends on fossil fuels, for this sector there has been a great number of research works. Charles et al. (2011) establish that the future of road transport, being currently reliant on carbon-based liquid fuels, is largely unclear. They studied this sector from different perspectives by considering a single energy paradigm using electricity; and multiple energy sources like electricity, biofuels, fossil fuels, hybrid electric vehicles and hydrogen fuel cells. In their work they include countries having diverse characteristics: two developed regions like the European Union and Australia; and two developing ones, sub-Saharan Africa and China. In the conclusions the authors indicate that energy diversity for road transport has emerged as a solution, from a short- to medium-term perspective, for the challenge of energy security, where diversification is potentially better. Besides, some other benefits can be obtained such as promoting competition, fostering innovation and mitigating lock-in. Ridjan et al. (2013) pointed out that transport, compared with other sectors, is still heavily dependent on oil displaying rapid growth in the last decades. The most promising sources are biofuels along with electricity. The biofuels produced from biomass have problems like: land use shortages, limited availability, and interference with food production. They specify that is essential to make a detailed analysis of this sector in order to match the demand and meet the criteria of a 100% renewable energy system in 2050. Lindfeldt et al. (2010) investigated the road transport system based on renewable resources for Sweden with the purpose to illustrate how such a system could be designed to avoid dependency on imports. They consider a decrease on demand due to technical and non-technical means of improving vehicle fuel economy while in the supply side; biofuels and synthetic fuels produced from renewable electricity are discussed. They conclude that biomass potential could cover from one fifth up to half of the energy demand after considering strong demand-side measures; and the use of renewable electricity in the transport sector is needed to cover the rest of the demand, either in the form of synthetic fuels from renewable electricity (methane or methanol), or, when mature technology is available, hydrogen and/or battery electric vehicles. Von Blottnitz and Curran (2007) present a review of assessments for bio-ethanol as a transportation fuel evaluating the net energy, greenhouse gas and environmental life cycle perspectives. They show up that some of the previous reviews done in the area are unfavorable from these perspectives while others are in the opposite direction. They study forty-seven published assessments comparing bio-ethanol to conventional fuel on a life cycle basis. The authors conclude that the technology choices in process residue handling and in fuel combustion are keys in order to cover those issues. Seven of the reviewed studies evaluated a wider range of environmental impacts, including resource depletion, global warming, ozone depletion, acidification, eutrophication, human and ecological health, smog formation, etc., but they came up with divergent conclusions. The authors pointed out that there is now a strong evidence that all bio-ethanol production is mildly to strongly beneficial from a climate protection and a fossil fuel conservation perspectives. Fuel ethanol produced from sugar crops in tropical settings appears by far the most efficient in these categories from a land-use perspective. In the same direction Floudas et al. (2012) presents a review of the energy processes for liquid transportation fuels using single and hybrid feedstock. Specifically, they focus this work in the following processes: indirect liquefaction of coal to liquid (CTL), natural gas to liquid (GTL), biomass to liquid (BTL), coal and natural gas to liquid (CGTL), coal and biomass to liquid (CBTL), natural gas and biomass to liquid (BGTL), and coal, biomass, and natural gas to liquid (CBGTL). They analyze contributions that take into account among other issues the economic, life cycle and sensitivity analysis. The main products are gasoline, diesel, kerosene, methanol, and DME, with optional coproduction of electricity, hydrogen, and LPG. The authors pointed out that the strategic planning problem for both single and hybrid feedstock energy processes is an opportunity for researchers to investigate the long-term viability of each system; either one type or multiple type of plants can be considered for a certain region or country according to their resources. Guillén-Gosálbez and Grossmann (2009) presented the design of sustainable chemical supply chains in the presence of uncertainty in the life cycle inventory associated with the network operation. The design task is mathematically formulated as a bi-criterion stochastic mixed-integer nonlinear program (MINLP) that simultaneously accounts for the maximization of the net present value and the minimization of the environmental impact for a given probability level. The authors solved two illustrative examples showing the set of Pareto optimal that trade-off the environmental impact and profit. The article incorporates environmental concerns at the strategic level of supply Chain Management (SCM), they explicit consider uncertainties in the emissions released and feedstock requirements associated with the supply chain operation. From a methodological point of view, Liu et al. (2011) presented an overview of typical methodologies of energy systems engineering, comprising superstructure based modeling, mixed-integer linear and nonlinear programming, multiobjective optimization, optimization under uncertainty, and life-cycle assessment. They applied these methods in real-life energy systems of very different nature and scale like polygeneration energy systems, hydrogen infrastructure planning, energy systems in commercial buildings, and biofuel supply chains. In the conclusions, the authors claim that the generic modeling and optimization methodologies presented in the article are suitable for energy systems and could be added into the scope of “energy systems engineering”. Acreche and Valeiro (2013) address the sustainability of sugar and ethanol production from a non-vertical integrated sugarcane industry in Argentina. The paper calculates the energy and greenhouse gas (GHG) emission balances. They consider in the model the following factors influencing these balances: gas-oil and nitrogen fertilizers used in the agricultural stage, natural gas consumed by the sugar mill, and sugarcane burning (only for GHG balance). The authors pointed out that the reduction in GHG emissions for this industry using ethanol in final blends of 95% gasoline and 5% ethanol is negligible, reductions can be obtained from a mixture of 90% of gasoline and 10% of ethanol, using 100% bagasse as fuel in mill boilers, ethanol being produced directly from sugarcane juice and not from molasses.

From the previous works, it can be seen the importance of producing energy by renewable sources without environmental impact. The idea behind the model proposed in this work is to provide an analysis instrument to make efficient and non-contaminant investments in energy. This article is organized as follows: first, the objective functions and constraints of the model are presented together with the scope and problem characteristics; then the scenarios proposed, the results obtained and their analyses are included becoming the larger section of this work; finally the conclusions, future directions and the nomenclature section are included.

2. Multiperiod multi-objective model

This article proposes a linear disjunctive multiperiod multi-objective model for planning investment in energy sources to satisfy 100% of the power demands for Argentina. The horizon time goes from 2010 until 2030. Two opposite objectives are considered, the first one is the maximization of the Net Present Value (NPV) installed capacity and operation of energy systems; while the second is the minimization of the GHG emissions. Fig. 1 shows the energy situation for Argentina at year 2010 according to Secretaria de Energía (2013), the table containing the values of this figure is provided as supplementary data. On the left hand side of the graph we have the primary energy sources, in the middle the converser plants transforming the primary into a form of usable energy, on the right hand side the markets where the energy flows. The line thickness represents the proportional contribution of each resource. It can be seen the great dependency on oil and natural gas (around 95%), which are non-renewable and GHG contaminants. For this study, the renewable energy sources included in the evaluation are those which Argentina has competitive advantages (Villalonga, 2013), the technologies have already been proved and got some level of maturity, as follows: (a) wind power, since there are several regions in the country where the wind flows almost continuously at a good average speed, like the Patagonia region in the south of the country, (b) biodiesel and bioethanol production due to the country is an important producer of several crops like soybean, sunflower, corn, sorghum, sugarcane, etc. (c) solar energy for commercial and residential heating, because in the last years a strong private industry offering solar heaters has emerged and (d) hydropower in the form of dams and hydrokinetic turbines;

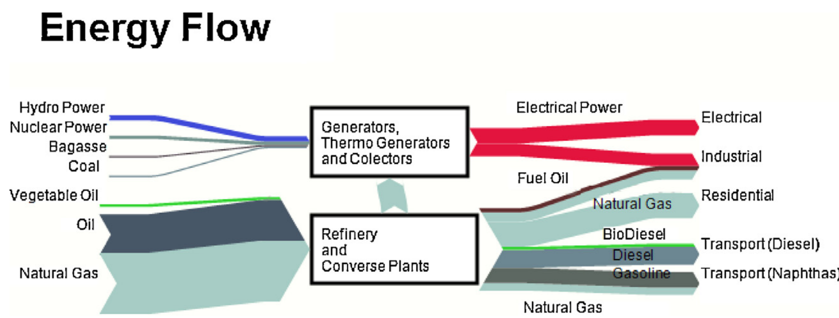

Fig. 1. Energy sources, energy converser plants and markets for Argentina.

this last resources is included given that several country' regions have important rivers with continuous streams at good speed. It must be taken into account that this technology does not have the maturity of some others. Non renewable sources contemplated in the model are mainly oil, natural gas and nuclear power, since they contribute to around 95% of the energy matrix. Conversion plants comprises bioethanol, biodiesel and petroleum refineries, wind-power and hydrokinetic farms, nuclear power plants, solar collectors and thermo electrical plants. Markets are industrial, domestic and commercial both consuming electricity, heating and some other uses, heavy and light transportation.

2.1. First objective (economic)

The minimization of the net present value is represented by Eqs. (1) and (2).

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

$$CSF_{i,k,t} = (P_{i,k,t} - CO_{i,k,t})x_{i,k,t} \cdot hr - CI_{i,k,t} - CS_{i,k,t} \quad \forall t; \forall (i,k) \in Markets_{i,k} \tag{2}$$

In Eq. (1), 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. The second term $NT.CA_{i,k,t}$ 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.

In Eq. (2) we express each cash flow $CSF_{i,k,t}$ like the annual financial balance. The term $P_{i,k,t.}\ x_{i,k,t}$ represents the revenues obtained by the source i, market k, period t, where P is the sale price, $x_{i,k,t}$ is the hourly amount of energy produced by source i, market k, period t, the term $CO_{i,k,t.}\ x_{i,k,t}$ 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 production of the plant for source i, market k, period t ($x_{i,k,t}$) and the annual operation hours of the plant (hr), $CI_{i,k,t}$ is the investment cost for a new installation; while $CS_{i,k,t}$ is the start-up cost of a new installation (considered only once in the life of a new plant) both calculated for source i, market k, period t.

The calculation of depreciation for Argentina is made considering 85% of the total cost of the property divided by the lifetime years of the asset. It is very common that financial life of an asset rarely matches the real lifetime. This is the reason because we have extended the productive life of the investments along the horizon of the study but their rates are limited. This is posed in Eqs. (3)–(5).

$$CA_{i,k,t} = 0 \quad , \forall t \le T_{i,k} \quad \forall (i,k) \in Markets_{i,k} \tag{3}$$

$$CA_{i,k,t} = \frac{\alpha_{Dep} \cdot CI_{i,k,t-T_{i,k}}}{TVU_{i,k}} + CA_{i,k,t-1} \quad , (T_{i,k} + TVU_{i,k}) \ge t > T_{i,k} \quad \forall (i,k) \in Markets_{i,k} \tag{4}$$

$$CA_{i,k,t} = \frac{\alpha_{Dep} \cdot (CI_{i,k,t-T_{i,k}} - CI_{i,k,t-(T_{i,k}+TVU_{i,k})})}{TVU_{i,k}} + CA_{i,k,t-1} \quad , \forall t > (T_{i,k} + TVU_{i,k}) \quad \forall (i,k) \in Markets_{i,k} \tag{5}$$

For new investments ($CI_{i,k,t}$) the depreciation is considered from its starting production time until they complete their period of life, which is represented by the parameter $TVU_{i,k}$. When no investments are made, the amortization cost ($CA_{i,k,t}$) is zero as indicated in Eq. (3). When $CI_{i,k,t}$ is different to zero, Eq. (4) calculate the value of the depreciation considering the investment cost using a straight line method. In Eq. (4) it is important to take into account in the depreciation cost of period t the accumulation of depreciation from previous periods. Eq. (5) in addition to performing the same as Eq. (4), it deducts the depreciation of the investments that have already completed its $TVU_{i,k}$.

2.2. Second objective (environmental)

The other objective is the minimization of the GHG emissions modeled as epsilon constraints (ε constraints) measured via a set of parametric values. For this case two approaches are proposed. The first one is represented by Eq. (6) which restricts the total GHG emissions evaluated in the horizon time:

$$\sum_k \sum_t XGEI_{k,t} \le \varepsilon \cdot \sum_k \sum_t GGEI_{k,t}^{up} \tag{6}$$

In Eq. (6), $XGEI_{k,t}$ corresponds to the amount of emissions for a given market k, in period t of all sources i, which is calculated by Eq. (7):

$$XGEI_{k,t} = \sum_{i \in Market_{i,k}} fGEI_{i,k} \cdot x_{i,k,t} \cdot hr \tag{7}$$

where $fGEI_{i,k}$ is the emissions generation factor taken from Intergovernmental Panel on Climate Change (2006), and tabulated in Table 1. In Eq. (6), ε is a parameter whose value is between 0 and 1, and $GGEI_{k,t}^{up}$ is a calculated upper bound value for the emissions, which is determined by Eq. (8) with the solution obtained with the model ($x_{i,k,t}^{Sol}$) without including any constraint related with

Table 1
GHG Emission Factor.

		GHG Emission Factor (tCO_2/m^3) ($fGEI_{i,k}$)	GHG Emission Factor (tCO_2/TJ) (includes oxidation factor)
Naphtha	Transport	2535.462	72.9
Gas Oil	Transport	2642.882	73
Fuel Oil	Electricity	3064.579	76
Natural Gas	Transport	0.022	56
Natural Gas	Electricity	0.022	56
Natural Gas	Residential	0.022	56

emissions. Results obtained for variables $x_{i,k,t}$ and $x^{Sol}_{i,k,t}$ are provided as supplementary data.

$$GGEI^{up}_{k,t} = \sum_{i \in Market_{i,k}} fGEI_{i,k} \cdot x^{Sol}_{i,k,t}.hr \tag{8}$$

The second approach is represented by Eq. (9) and takes into account the minimization of the GHG emissions for each time period instead in the whole horizon time. The main difference between Eqs. (9) and (6) is the summation over the time periods of both terms.

$$\sum_k XGEI_{k,t} \leq \varepsilon \cdot \sum_k GGEI^{up}_{k,t} \quad \forall t > 5 \tag{9}$$

Eq. (9) is evaluated after period 5 to allow investments in renewable energies in previous terms, in this way; the problem solution can reach the goal in emissions without infeasibilities.

2.3. Constraints

The model must satisfy Argentina' energy demands for electricity, transportation and heating. Although demands can be an uncertain parameter, for this study deterministic curve for each source and market was calculated using historical statistics data collected by several government and independent organizations. The approximations made are linear and posed according to Eq. (10):

$$D_{k,t} = D0_k + \alpha_k \cdot (t-1) \quad \forall k, \forall t \tag{10}$$

Energy demand for market k, period t ($D_{k,t}$) is equal to the needs of the initial period ($D0_k$) plus an increase coefficient (α_k) times the number of periods minus 1. The initial demand for each market at year 2010 is showed in Table 2. The demand values of previous periods considered to get the α_k parameter are provided as supplementary data.

The energy supply is stated by Eq. (11) where the summation of the energy production of sources i (represented by the term $f_{i,k} \cdot x_{i,k,t} \cdot hr$) must be equal to the demand for a market k in period t.

$$\sum_{i \in Markets_{i,k}} f_{i,k} \cdot x_{i,k,t} \cdot hr = D_{k,t} \quad \forall t; \forall k \tag{11}$$

In Eq. (11) $f_{i,k}$ is a parameter that takes into account the performance and unit conversion factor between source i to market k. This is done in order to express all energy flows in the same unit. Data used for this factor are given as supplementary data.

Table 2
Initial Demand ($D0_k$).

Transport Naphtha	13482594.6	m^3
Transport Diesel	9769182.91	m^3
Electricity	71172765	MWh
Residential	8481395000	m^3

The energy flow for source i must be less than or equal to the installed capacity $Cap_{i,k,t}$ for that supply for market k time t (Eq. (12)).

$$f_{i,k} \cdot x_{i,k,t} \leq Cap_{i,k,t} \quad \forall t; \forall (i,k) \in Markets_{i,k} \tag{12}$$

The installed capacity can vary from period to period according to the investments made which are discrete decisions formulated by means of disjunction (13).

$$\left[\bigvee_{r=1..R} \begin{bmatrix} w_{i,k,t-T_{i,k}} \\ y_{r,i,k,t-T_{i,k}} \\ CI_{i,k,t-T_{i,k}} \geq Cm_{r,i,k} \\ ICap_{i,k,t} \leq Imax_{r,i,k} \\ CS_{i,k,t-1} \geq CSm_{r,i,k} \end{bmatrix} \right] \vee \begin{bmatrix} \neg w_{i,k,t-T_{i,k}} \\ CI_{i,k,t-T_{i,k}} = 0 \\ ICap_{i,k,t} = 0 \\ CS_{i,k,t-1} = 0 \end{bmatrix}$$

$$\forall t > T_{i,k}; \quad \forall (i,k) \in Markets_{i,k} \tag{13}$$

Boolean variable $W_{i,k,t} - T_{i,k}$ is used to establish if a new investment is performed for source i, market k in period $t - T_{i,k}$. The difference represented by $t - T_{i,k}$ expresses the gap between the time t the investment decision is made and the moment it start the production ($T_{i,k}$). Once the investment is decided, another discrete choice is made employing Boolean variable $y_{r,i,k,t} - T_{i,k}$ to determine the capacity ($ICap_{i,k,t}$) and cost ($CI_{i,k,t} - T_{i,k}$) of the new asset; which are defined thorough discontinuous functions, ranging over several intervals (r = 1..R). Data used for the investment cost intervals are provided as supplementary data. Note that in this case only one term must be true. In disjunction (13), the plant capacity is limited by the parameter $Imax_{r,i,k}$, which is a maximum value for that term; similarly the amount to invest has a lower bound limited by parameter $Cm_{r,i,k}$. $CS_{i,k,t}$ (the start-up cost explained before) also has a lower bound restricted by $CSm_{r,i,k}$.

For some sources i for market k at time $T_{i,k}$ we have an initial installed capacity equal to $Cap0_{i,k}$(Table 3); this situation is defined by Eq. (14):

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

Table 3
Initial installed capacity $Cap0_{i,k}$.

Oil	Industrial	11200	m^3/h
Fuel oil	Electricity	0.45946	MW
Fuel oil	Industrial	1200000	m^3/h
Natural gas	Transport	326018.371	m^3/h
Natural gas	Electricity	14358	MW
Natural gas	Residential	1026700.47	m^3/h
Natural gas	Industrial	3.55E+10	m^3/h
Bio diesel	Transport	315.489	m^3/h
Bio ethanol	Transport	38.09	m^3/h
Wind power	Electricity	80	MW
Nuclear power	Electricity	10180	MW

Table 4
Initial reserves for 2010 ($RD0_i$) (INDEC, 2010).

Oil	415914000	m^3
Natural gas	4.451E+11	m^3
Nuclear power	1.05E+08	kg

For time t greater than $T_{i,k}$ the capacity can be increased according to the investments of disjunction (13), this is posed by Eq. (15).

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

Depending on the source, the capacity to provide energy has an upper bound limit according to the natural resources available in the country. For non-renewable energy sources ($i \in NR$), Eq. (18) states that the production of energy for sources i at time t for all its markets k must be less than the available reserves for that period $RD_{i,t}$. Reserves are determined for each period in Eq. (16) at the beginning of the time period and for Eq. (17) for the rest of the periods. The initial reserves for the non-renewable sources are tabulated in Table 4.

$$RD_{i,t=1} = RD0_i \quad \forall i \in NR \tag{16}$$

$$RD_{i,t} = RD_{i,t-1} - \sum_{k \in Market_{i,k}} x_{i,k,t-1} \cdot hr \quad \forall i \in NR, \forall t > 1 \tag{17}$$

$$\sum_{k \in Market_{i,k}} x_{i,k,t} \cdot hr \leq RD_{i,t} \quad \forall i \in NR, \forall t \tag{18}$$

For renewable supplies constraint (19) establishes the capacity limits by means of parameter CD_i.

$$\sum_{k \in Markets_{i,k}} \frac{Cap_{i,k,t}}{f_{i,k}} \leq CD_i \quad \forall t; \quad \forall i \notin NR \tag{19}$$

CD_i (Table 5) takes different values according to the renewable source, for biodiesel it corresponds to the 2% of the total soybean harvested multiplied by the estimated yield of this crop into biodiesel. Data were taken from Argentina' National Institute of Agriculture (INTA – Instituto Nacional de Tecnología Agropecuaria, 2013), a similar estimate was made for bioethanol from sugarcane and corn as feedstock.

The installation of windmills is restricted by the free area where wind blows in average 80% of the time at the operation ranges of wind turbines, this data was extracted from Argentina' Renewable Energy Association (Cámara Argentina de Energía Renovables, 2013), which provides this information. The bound on the use of solar energy for commercial and residential heating was determined taking the value of the solar radiation received on an horizontal surface with a strong an constant value during the year; and taking the number of possible residences in the area. This data was given by Argentina' Renewable Energy Association (Cámara Argentina de Energía Renovables, 2013) and Argentina' National Institute of Statistics (Instituto Nacional de Estadísticas y Censos, 2013).

Table 5
Maximum capacity (CD_i).

Bio diesel	1108.853	m^3/h
Bio ethanol	232.722	m^3/h
Win power	9267073.2	MW
Solar	712288.529	mGN^3/h
Hydro power	16	MW

Table 6
Relationships sources-technologies-markets.

Sources	Technologies	Markets
Oil and/or derivates Natural gas Bio fuels	Internal combustion engine	Transport
Oil and/or derivates Natural gas Nuclear power	Thermal generators	Electricity
Wind power	Wind Farms	
Hydraulic power	Hydraulic turbines Hydrokinetic turbines	
Natural gas	Burners	Residential and commercial
Solar power	Collectors	

Model that evaluates the total GHG emission in the horizon time (model TEM) is composed of Eqs. (1)–(7), (10)–(19).

Model evaluating the annual GHG emission in the horizon time (model AEM) is composed of Eqs. (1)–(5), (7), (9)–(19).

Table 6 shows the links among energy sources, technologies and markets.

The disjunctive linear models were relaxed into a MILP using the convex-hull and solved with CPLEX 12.3 using GAMS. The statistics about models execution are set in Table 7.

3. Results

For each model (TEM and AEM) we have defined 20 different scenarios changing the value of the ε parameter.

For TEM model, the ε value goes from 0.8, for scenario 1, until 0.601, for scenario 20.
For AEM model, the ε value goes from 0.8, for scenario 1, until 0.615, for scenario 20.

The reasons of having those values intervals are that in both cases, for ε values between 0.8 and 1.0 the results obtained with the model does no change; and for ε values below 0.601 (TEM) and 0.615 (AEM) the solution of the models were infeasible, meaning that it is not possible to satisfy the GHG emissions with the data and constraints imposed to them. The ε values for the scenarios are showed in Table 8.

Fig. 2 shows the NPV obtained for each model, in the y axis is shown the NPV measured in million of US dollars (MUS$) and the x axis show the emissions in Ton of CO_2, each point in the graph corresponds to one scenario. Model TEM obtains better economic results since it has more freedom to adjust the investment and the emission values over the whole time horizon and achieves a better profit, while AEM adjusted year by year the emanation of GHG, without the possibility of waiting the proper economic moment to make the investments. In model AEM, from scenario 16 until scenario 20 emissions are constant considering the whole time horizon, in those scenarios the model generates more GHG emanation from period 1 to period 5 where no constraints in contamination are imposed, while in the rest of the periods they achieve its upper limit, the explanation for this behavior is that the model maximizes the economic objective.

Table 7
Model statistics.

MODEL	AEM	TEM
Equations	6801	4506
Variables	7346	5050
Discrete variables	2350	2350
CPU time (per scenario)	<1 s	<1 s

Table 8
ε value for each scenario.

Scenario	1	2	3	4	5	6	7	8	9	10
TEM	0.800	0.790	0.779	0.769	0.758	0.748	0.737	0.727	0.716	0.706
AEM	0.800	0.790	0.781	0.771	0.761	0.751	0.742	0.732	0.722	0.712
Scenario	11	12	13	14	15	16	17	18	19	20
TEM	0.695	0.685	0.674	0.664	0.653	0.643	0.632	0.622	0.611	0.601
AEM	0.703	0.693	0.683	0.673	0.664	0.654	0.644	0.634	0.625	0.615

Table 9
Common Investments made for model TEM and AEM.

		2010		2011		2012		2013		2014		2016	
		MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
Biodiesel	Transport	144	136	144	136	144	136	144	136	144	136		
Bioethanol	Transport												
Wind Power	Electricity	1868	418	1868	418							1868	418
Solar Power	Commercial-Residential	414	662										
Hydrokinetic	Electricity	18	1.5										

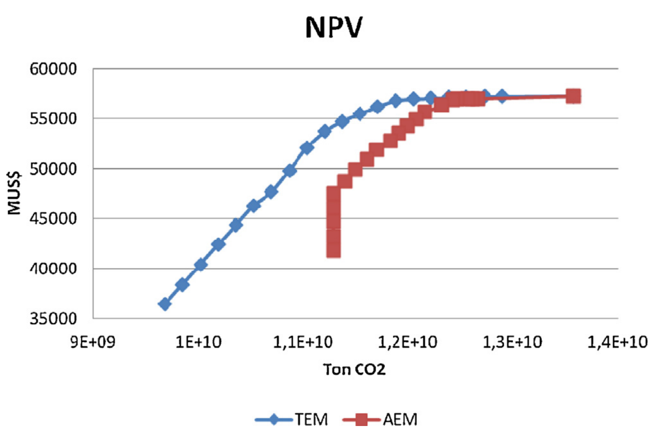

Fig. 2. Net present value obtained for each scenario in both models.

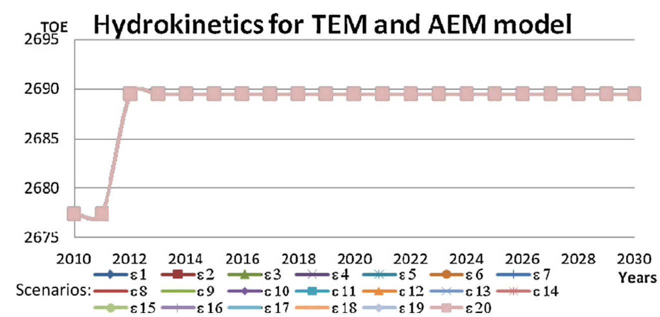

Fig. 4. Hidrokinetic energy production (in TOE) vs. time period (year) for TEM and AEM model.

Table 9 presents the common investments made (in amount, capacity and time) for both models. In Table 9, and the other tables presented in this work investments are shown in million of US dollars, and capacity in tons of oil equivalent (TOE).

From Table 9, can be observed that for solar energy for domestic and commercial heating, and for hydrokinetic turbines to produce electricity, investments are made at the beginning of the horizon time and they reach the upper bound limit of its capacity. The reason is that they are economical sources and do not have emanation of GHG. For both models the behavior is the same (see Figs. 3 and 4). Note that in those figures all 20 scenarios are included but they are hidden by scenario 20 because results are same for all of them. The weakness of these technologies is that they only cover a limited amount of the total energy used.

In Fig. 3 until Fig. 15, the x axis represents the energy production measured in tons of oil equivalent (TOE) and in the y axis the year where production of energy starts a new value; on the figures all 20 scenarios are included.

Wind power mills are used for the electricity market. Table 9 shows that investments are made at the beginning and the middle of the time period for both models. The behavior is the same considering total (TEM) and annual emissions (AEM) of GHG (Fig. 5). Investment cost of wind mills is expensive but they have an important positive consequence in the environmental objective, without using the capacity of this source it is not possible to reach the diminution in the GHG emissions. This is the main reason because this source is exploited. Note that in this case, all scenarios gave the same results.

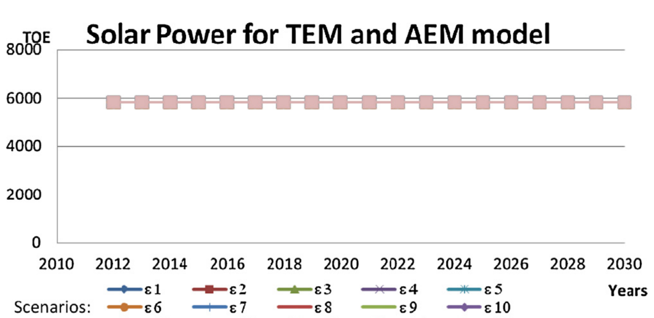

Fig. 3. Solar energy production (in TOE) vs. time period (year) for TEM and AEM model.

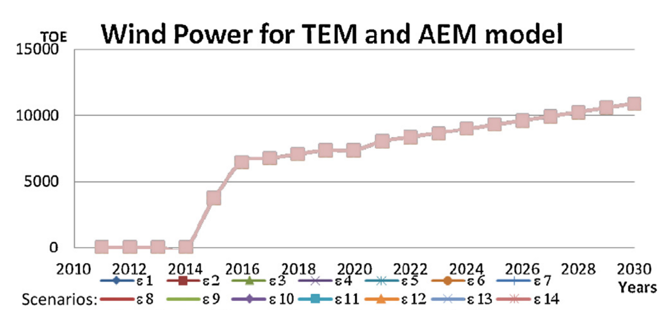

Fig. 5. Wind power energy production (in TOE) vs. time period (year) for TEM and AEM models.

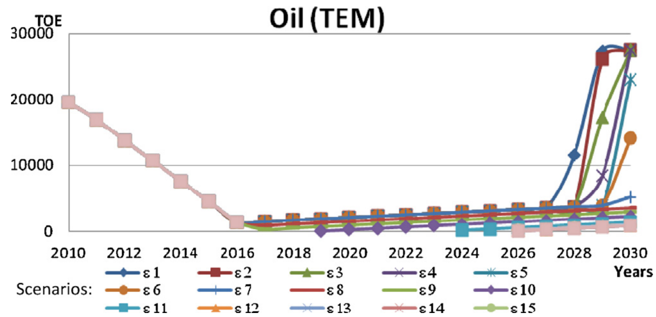

Fig. 6. Petroleum energy usage (in TOE) vs. time period (year) for TEM model.

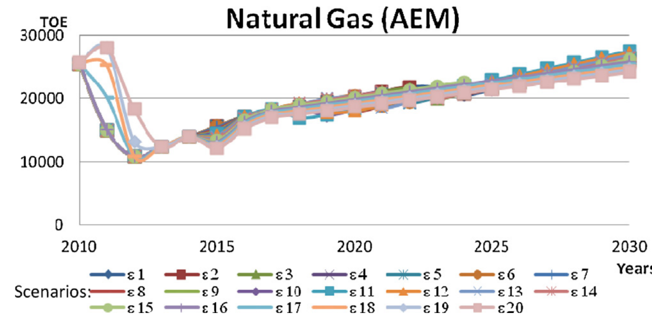

Fig. 9. Natural gas usage (in TOE) vs. time period (year) for AEM model.

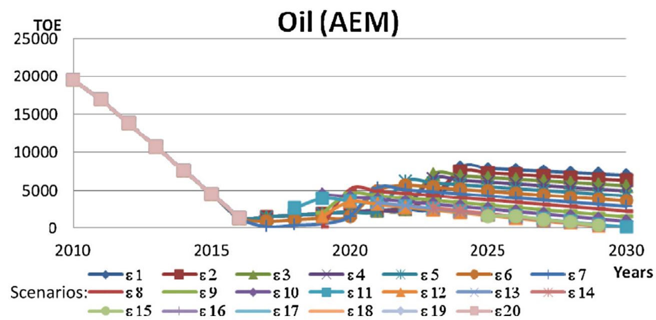

Fig. 7. Petroleum energy usage (in TOE) vs. time period (year) for TEM model.

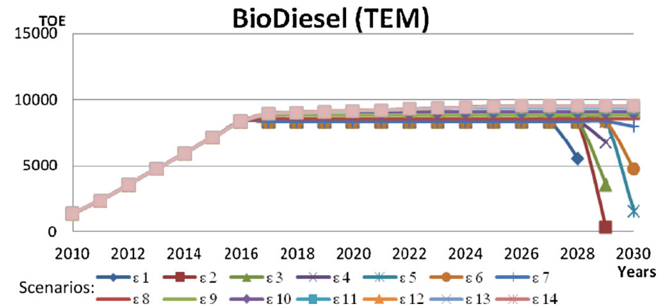

Fig. 10. Biodiesel usage (in TOE) vs. time period (year) for TEM model.

Oil is used mainly for the transport sector; its utilization is strongly restricted in both models at the beginning of the horizon time until year 2016, where the investment in renewable and non-contaminant sources start the full production. This is done to satisfy the constraints imposed in the emission and its environmental impact; it is notorious how the use of oil increases from year 2027–2030 for model TEM (Fig. 6) and for high ε values (0.8–0.75) where more emissions are allowed. The reason for this behavior is economic; more revenues are obtained using oil on those years than the previous periods. In the AEM model (Fig. 7), after year 2016, the emissions are annually adjusted according to the ε value, for high ε values more oil derivatives are employed for energy production.

Natural gas is the cheapest and more efficient energy source (talking about economic terms) and is employed for several markets: electricity, heating and transport. Due to these conditions, the model always tries to make use of this source for those markets. For model TEM (Fig. 8), after a decrease in the amount consumed to satisfy the emanation constraints, it start yearly increased to obtain more profit. At the end of the horizon time and for less restrictive scenarios in emanation, it has similar behavior than the petroleum case. For the AEM model (Fig. 9), since in the first 5 years emissions are not controlled and for the more restrictive emissions scenarios, it increases the use of natural gas at the beginning of the period to satisfy economic energy supply, then it is adjust year by year to satisfy the environmental objectives.

Table 10 shows the investment made in amount of money and capacity (in TOE) for biodiesel production for both models, TEM and AEM, after year 2014. Both models present the same investments from 2010–2014 (see Table 9).

Since the use of biodiesel is restricted to heavy transportation sector which consumes a great proportion of the petroleum, the behavior of this source is the opposite considering both models. For TEM model (Fig. 10) in the earliest years of the time period, the use of biodiesel deeply increases to diminish de emanation of GHG and then is adjusted to satisfy the environmental restrictions. At the end of the period it diminishes to obtain more profit for those scenarios that allow more emissions which is the contrary of the petroleum use. For the annual emissions model (Fig. 11) it increases the use until year 2015, and then adjust year by year to satisfy the emanation constraints according to the scenario' constraints.

Bioethanol competes in the light transportation market with the use of gasoline and natural gas. From Table 11 can be seen that investments and start up production is spread along the time horizon. When more restrictions are imposed in GHG emissions new plants are installed closer to the beginning of the time horizon. This situation is shown in Fig. 12.

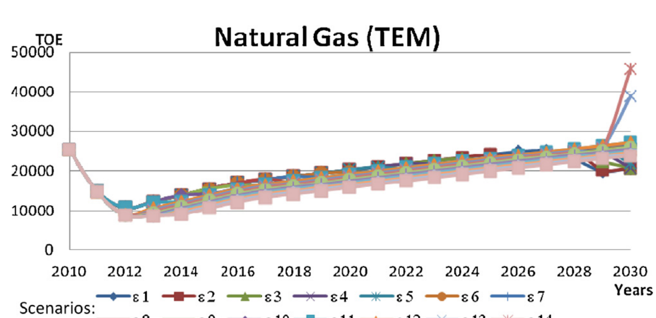

Fig. 8. Natural gas usage (in TOE) vs. time period (year) for TEM model.

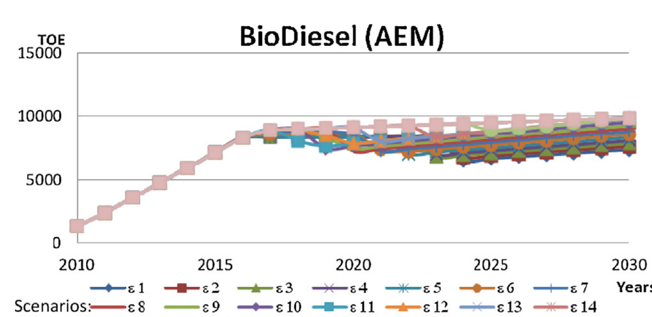

Fig. 11. Biodiesel usage (in TOE) vs. time period (year) for AEM model.

Table 10
Investments made for model TEM and AEM (after 2014).

	TEM				AEM													
	2015		2024		2015		2023		2024		2025		2026		2027		2028	
	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
1	69	25			69	25												
2	69	25			69	25												
3	69	25			69	25												
4	69	25			69	25												
5	69	25			69	25												
6	69	25			69	25												
7	69	25			115	56												
8	69	25			137	97												
9	115	56			137	97											69	25
10	137	97			137	97									137	97		
11	144	136			137	97					69	25	144	136				
12	144	136			137	97					144	136						
13	144	136			137	97	69	25					137	97				
14	144	136			144	136									115	56		
15	144	134			144	136									115	56		
16	144	134			144	134			69	25	69	25	69	25				
17	144	134			144	136			69	25			69	25				
18	144	134			144	136			115	56								
19	144	134			144	136			69	25							69	25
20	144	136	69	25	144	136			115	56								

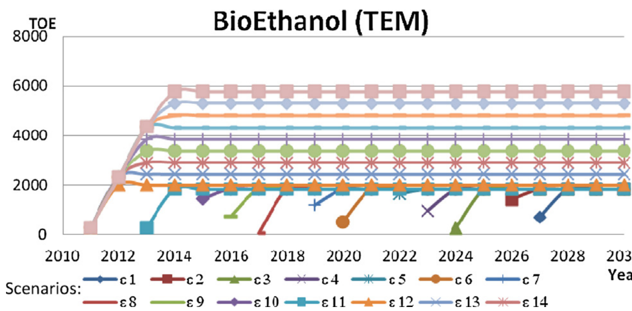

Fig. 12. Bioethanol production (in TOE) vs. time period (year) for AEM model.

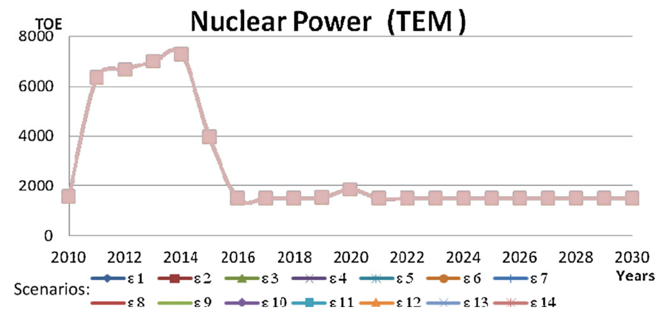

Fig. 14. Power production by nuclear plants (in TOE) vs. time period (year) for TEM model.

For model AEM the behavior is a bit different than TEM. Investments to diminish emissions are made along the time horizon following the scenario constraints (Table 12); the installed capacity is used according to the situation needs. In the most restrictive environmental scenarios, new investments are made at the end of the horizon time to adjust the emissions and to improve the profit. This situation can be seen in Fig. 13.

Nuclear power is used for the electricity market. Argentina has an installed capacity which is not employed in full. In this approach, this technology does not contribute to GHG emissions; the treatment of nuclear wastes is penalized in the operational cost. No new investments are made for this source in the horizon time due to the expensive installation and operational cost; and also the long construction and start time. The capacity installed is employed in full on the earliest periods to satisfy electricity demands and diminish GHG emanation, in year 2016, where wind mills start producing equivalent energy, the use of this nuclear resource to generate electricity is decreased to a minimum. This behavior is similar in both models with some particularities in the AEM formulation which is more scenarios dependable (see Figs. 14 and 15).

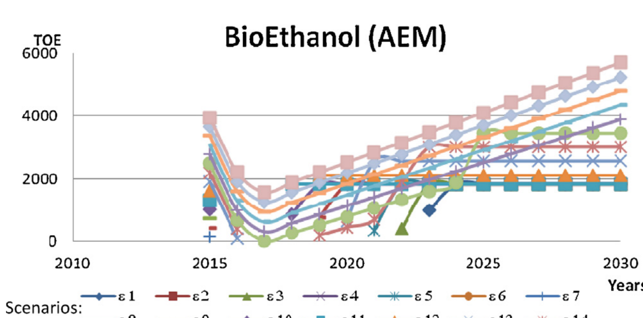

Fig. 13. Bioethanol production (in TOE) vs. time period (year) for AEM model.

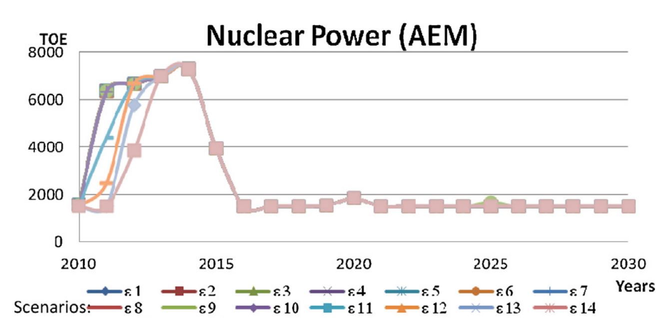

Fig. 15. Power production by nuclear plants (in TOE) vs. time period (year) for AEM model.

Table 11
Investments made for bioethanol in amount of money(MUS$) and capacity (TOE) for TEM model.

	2010		2011		2012		2013		2014		2016		2017		2018		2020		2021		2023		2024		2025	
	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
1																									485	231
2																							485	231		
3																					485	231				
4																			485	231						
5																	485	231								
6															485	231										
7													485	231												
8											485	231														
9									485	231																
10							485	231																		
11			485	231																						
12	485	231																								
13	485	231	231	56																						
14	485	231	385	108																						
15	485	231	462	163																						
16	485	231	485	231																						
17	485	231	485	231																						
18	485	231	485	231	231	56																				
19	485	231	485	231	385	108																				
20	485	231	485	231	462	163																				

Table 12
Investments made for bioethano in amount of money and capacity for AEM model.

	2012		2013		2017		2018		2019		2020		2021		2022		2023		2024		2025		2027	
	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
1													485	231										
2													485	231										
3											485	231												
4											485	231												
5									485	231														
6									485	231														
7							485	231																
8			231	56			462	163																
9			231	56	462	163																		
10			485	231																				
11			485	231																				
12			485	231																				
13			485	231					231	55														
14			485	231									385	108										
15	231	56	485	231											385	108								
16	231	56	485	231															231	56	485	231		
17	385	108	485	231															231	56	231	56	231	56
IS	462	165	485	231															462	163				
19	462	165	485	231															485	231				
20	485	231	485	231													485	231						

4. Conclusions

In this paper, a multiperiod multi-objective linear disjunctive model is proposed for the evaluation of different scenarios about planning investments in energy generation. The idea of the model is to provide an instrument for energy decision makers to evaluate different scenarios, in order to analyze the economic and environmental impact (mainly GHG emissions) of different renewable and non-renewable power supply in order to satisfy 100% of the energy market. With this tool, it is possible to visualize at present day the possibility of defining subsidies and some other measures such as incentives, tax reduction, penalties, etc., for energy generation in the long-term. The model can be adapted to any geographical region by including/eliminating components in the set of sources, transformation plants and/or energy markets. An important amount of time and effort was made to gather statistical information about consumes, prices, installed capacities, etc. Results show the trade-offs between both objectives analyzed balancing the economical with environmental issues. The use of natural gas for electricity sector, is maximized since is the most economical energy source covering several markets, while the non contaminant options like solar, hydrokinetic and wind power sources are planned to invests at the beginning of the time period to satisfy the GHG emanation constraints. The investments in biodiesel and bioethanol to replace the use of petroleum derivatives for the transportation market, based on the diminution of GHG emissions are adjusted along the time horizon analyzed. As can be seen in Table 10, after initial investments in transformation plants for biodiesel to satisfy GHG emissions constraints, other investments are made along the horizon time to adjust both economical and environmental objectives. Tables 11 and 12 show the results for bioethanol case; this fuel is not economically attractive for light transportation compared to oil derivatives, and that is the reason because investments are distributed along the time horizon where better profits and more restrictive GHG gas emissions are required.

Future work contemplates the inclusion of uncertainties in the optimization model. Energy production in a long horizon time can have several uncertainties caused by different aspects of the problem. Uncertainties may be originated by the non constant availability of wind and solar radiation, an insufficient crops production and also the undetermined demand and prices of the energy.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compchemeng.2014.05.006.

References

Acreche M, Valeiro A. Greenhouse gasses emissions and energy balances of a non-vertically integrated sugar and ethanol supply chain: a case study in Argentina. Energy 2013;54:146–54.

Bernardi A, Giarola S, Bezzo F. Optimizing the economics and the carbon and water footprints of bioethanol supply chains. Biofuels Bioprod Biorefining 2012;6:656–72.

Bernardi A, Giarola S, Bezzo F. Spatially explicit multiobjective optimization for the strategic design of first and second generation biorefineries including carbon and water footprints. Ind Eng Chem Res 2013;52:7170–80.

Cámara Argentina de Energías Renovables, [visited 10.05.13] http://www.argentinarenovables.org/index.php

Careri F, Genesi C, Marannino P, Montagna M, Rossi P, Siviero I. Generation expansion planning in the age of green economy. IEEE Trans Power Syst 2011;26:2214–23.

Charles MB, To H, Gillett P, von der Heidt T, Kivits R. Transport energy futures: exploring the geopolitical dimension". Futures 2011;43:1142–53.

Cicea C, Marinescu C, Popa I, Dobrin C. Environmental efficiency of investments in renewable energy: comparative analysis at macroeconomic level. Renew Sustain Energy Rev 2014;30:555–64.

Fazlollahi S, Mandel P, Becker G, Maréchal F. Methods for multi-objective investment and operating optimization of complex energy systems. Energy 2012;45:12–22.

Floudas C, Elia J, Baliban R. Hybrid and single feedstock energy processes for liquid transportation fuels: a critical review. Comput Chem Eng 2012;41:24–51.

Giarola S, Zamboni A, Bezzo F. Spatially explicit multi-objective optimisation for design and planning of hybrid first and second generation biorefineries. Comput Chem Eng 2011;35:1782–97.

Guillén-Gosálbez G, Grossmann IE. Optimal design and planning of sustainable chemical supply chains under uncertainty. AIChE J 2009;55:99–121.

IEA. Annual Report 2012. International Energy Agency (IEA); 2012.

IEA. World Energy Outlook. Chapter 6: Renewable Energy Outlook. International Energy Agency (IEA); 2013.

Instituto Nacional de Estadísticas y Censos (INDEC), [accessed 10.05.13] http://www.indec.mecon.ar/

Instituto Nacional de Tecnología Agropecuaria, [accessed 10.05.13] http://www.inta.gov.ar/iir/info/documentos/energia/indicadores_biodiesel.pdf

IPCC. Summary for policymakers. In: Edenhofer O, PichsMadruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, von Stechow C, editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge/United Kingdom/New York, NY, USA: Cambridge University Press; 2011.

Intergovernmental Panel on Climate Change.Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K, editors. 2006 IPCC guidelines for national greenhouse gas inventories; 2006 [accessed 10.5.13] http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

Lindfeldt EG, Saxe M, Magnusson M, Mohseni F. Strategies for a road transport system based on renewable resources – The case of an import-independent Sweden in 2025. Appl Energy 2010;87:1836–45.

Liu P, Georgiadis M, Pistikopoulos E. Advances in energy systems engineering. Ind Eng Chem Res 2011;50:4915–26.

Ridjan I, Mathiesen BV, Connolly D, Duić N. The feasibility of synthetic fuels in renewable energy systems. Energy 2013;57:76–84.

Tang A, Chiara N, Taylor J. Financing renewable energy infrastructure: formulation, pricing and impact of a carbon revenue bond. Energy Policy 2012;45:691–703.

Von Blottnitz H, Curran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. J Clean Prod 2007;15:607–19.

Wüstenhagen R, Menichetti M. Strategic choices for renewable energy investment: conceptual framework and opportunities for further research. Energy Policy 2012;40:1–10.

Secretaría de Energía de la República Argentina. Balances Energéticos. *BEN 2010*. [internet] Available at: http://energia3.mecon.gov.ar/contenidos/verpagina.php?idpagina=3366 [accessed 13.02.13].

Villalonga JC. Energías Renovables. ¿Por qué debería ser prioritario cumplir el objetivo del 8% al 2016? Fundacion AVINA; 2013, ISBN 978-987-25230-3-9.