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Highlights

► Electricity grid operating cost and life cycle greenhouse gas emissions minimization. ► Thermoelectric, hydroelectric, nuclear, solar PV and wind power plants considered. ► A bi-objective mixed integer linear programming problem is formulated and solved. ► Pareto optimal frontier is generated using the e-constraint solving method. ► Increment in grid operating cost to reduce life cycle GHG emissions is quantified.

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Operation of a national electricity network to minimize life cycle greenhouse gas emissions and cost

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ABSTRACT

A methodology to select the generation plants connected to the Argentinean electricity network and their operating loads is presented, minimizing life cycle greenhouse gases (GHG) emissions and operating cost. Mixed integer linear programming problems are formulated and solved in GAMS. The electricity generation grid has different fossil fuel thermoelectric, hydroelectric, nuclear, solar photovoltaic and wind power plants. Binary operating variables represent discrete decisions to select the power plants connected to the grid and the type of fossil fuel burnt in thermoelectric plants. Continuous operating variables allow the selection of the optimal load for each generation unit. Significant reductions in life cycle GHG emissions and operating cost are achieved in the operation of the Argentinean electricity network, providing relevant information to support a decision-making process.

Q1 1. Introduction

In the last decade, the role of energy generation in economical and social development has been recognized. However, the current energy supply systems do not follow sustainable principles, as it is the case of electricity generation. The main source of greenhouse gases (GHG) emissions is the combustion of fossil fuels although these emissions are also present in the entire life cycle of many products or services, and electricity is not an exception. Weisser [1] presented an exhaustive work on life cycle GHG emissions of the energy generation, paying special attention to fossil fuel, nuclear and renewable energy technologies in the European Union and Japan. Hashim et al. [2] minimize CO_2 emissions of the Ontario energy system; however the authors did not considered the life cycle CO_2 emissions due to upstream processes of each electricity generation plant.

Scientific Journals and articles dedicated to energy system optimization are increasing in the last few years. El-Halwagi et al. [3] solved an optimization problem that simultaneously considers profit maximization and environmental impact minimization applied to planning of a biomass conversion system. Elkamel et al. [4] proposes to solve a multi-objective non-linear optimization problem to assess the environmental and economic dispatch of energy markets, considering CO_2 life cycle emissions of the fuel supply chain. The classical economic problem of determining low-cost and reliable operation of a fossil fuel fired electric generator is coupled with an environmental objective function to minimize CO_2 emissions. Ren et al. [5] deals with multi-objective optimization considering the total operating cost and CO_2 emissions of solar photovoltaic, fuel cells and gas engine technologies.

Reduction of greenhouse gases (GHG) emissions using renewable technologies is presented by Dincer et al. [6].

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Nomenclature

G	electricity generation, Gwh
C_G	Electricity generation cost, 10^6 US$.
D	Interconnected system electricity demand, Gwh
d	power plant availability factor, dimensionless
F	Greenhouse gases stream, tons CO_{2e}
E	emission factor, tons CO_{2e}/Gwh
y	binary variable, selection variable
gwp	global worming potential

Supercripts

Max	Power plant maximum installed capacity
LB	Lower bound on the availability factor
a	Current value of the availability factor
l	life cycle stage
LC	Life cycle

Subscripts

q	Electricity generation technology
k	greenhouse gas: CO_2, CH_4, N_2O
f	fossil fuel: NG, natural gas, FO, fuel oil, GO, gas oil, C, coal
GHG	greenhouse gases

Sets

CC	Combined cycle power plants
F	Fossil fuel power plants
GT	Gas turbine power plants
NF	No fossil fuel power plants: H, hydroelectric, N, nuclear, Solar PV, Wind
ST	Steam turbine power plants

Greek symbols

β	maximum increment allowed for the availability factor

Martínez and Eliceche [7] analyzed the incidence of recycling a hydrogen rich stream, from the top of demethanizer column to the steam and power plant, in the reduction of GHG emissions. Eliceche et al. [8] minimize the life cycle GHG emissions of utility plants, extending the battery limits to include the life cycle emissions of imported natural gas and electricity. Martínez and Eliceche [9] dealt with economical and environmental objective functions simultaneously, implementing different bi-objective methodologies to select the operating conditions of utility plants.

In the present work, life cycle GHG emissions are estimated extending the limits of each electricity generation units to include the main burdens from raw material extraction to waste disposal. A similar approach was presented by Pasquevich et al. [10] applied to electrolytic hydrogen production and distribution for transportation purposes. The Argentinean electricity grid has coal (C), fuel oil (FO), gas oil (GO) and natural gas (NG) driven thermoelectric plants, nuclear and hydroelectric plants, wind and solar photovoltaic technologies have also been added to the interconnected system. Life cycle GHG emissions and generation cost of the national interconnected electricity network are minimized. The network generation cost includes the costs of fuels and maintenance of each power plant. A similar approach was successfully used to select the operating conditions of a steam and power plant by Martínez and Eliceche [11]. In this work life cycle GHG emissions and operating cost of the Argentinean electricity grid are minimized formulating and solving mixed integer linear optimization problems in GAMS [12]. The methodology presented leads to significant reductions in life cycle GHG emissions and operating cost of the Argentinean electricity network.

2. Electricity generation network modeling

The modeling of the Argentinean interconnected electricity system, adapted from Martínez [13], includes continuous and binary variables. Electricity generation of each power plant is modeled as a fraction of its installed capacity. Binary variables representing discrete decisions are introduced to select the power plants (fossil fuel based or not) connected to the grid and the alternative fossil fuel (NG, FO, GO or C) used in a given thermoelectric power plant. The mix of all the electricity generated provides electricity to the interconnected grid. The model considers the electricity generated by a certain power plant as a fraction of its maximum installed capacity, G^{Max}:

$$G(q, f) = G^{Max}(q, f) \times d(q, f) \quad \forall q \in F \tag{1}$$

$$G(q) = G^{Max}(q) \times d(q) \quad \forall q \in NF \tag{2}$$

Where $G(q,f)$ is the electricity generated in GWh, by power plant q burning fossil fuel f. All the fossil fuel driven power plants are included in the group F, including different technologies as gas and steam turbines as well as combined cycle units. $G(q)$ is the electricity generated by the power plant q which does not consume fossil fuels and belong to the group NF where nuclear, hydroelectric, wind and solar power plants are included, see Figs. 1–3. The variables $d(q,f)$ or $d(q)$ are the availability factor of each power plant. They express the ratio between the energy produced by a power plant in a given period of time and the energy that it would be generated by the power plant working at its maximum installed capacity during the same period of time. The availability factor of each power plant depends on random factors that limit the actual availability to supply electricity; then the availability factor is estimated with the historic behavior of each machine considering its average historical capacity.

In order to select the fossil fuel used in a certain power plant, it is necessary to introduce binary variables in the mathematical model. The binary variable $y_{q,f}$ takes the value 1 if the power plant q is burning the fossil fuel f and it is equal to 0 otherwise. The fact that a certain thermoelectric power plant could only work with an alternative fossil fuel, in a given time period, is modeled with the following equation:

$$\sum_f y_{q,f} \le 1 \tag{3}$$

Binary variables y_q are defined for the group of non-fossil fuel plants NF, to select which hydroelectric, nuclear or

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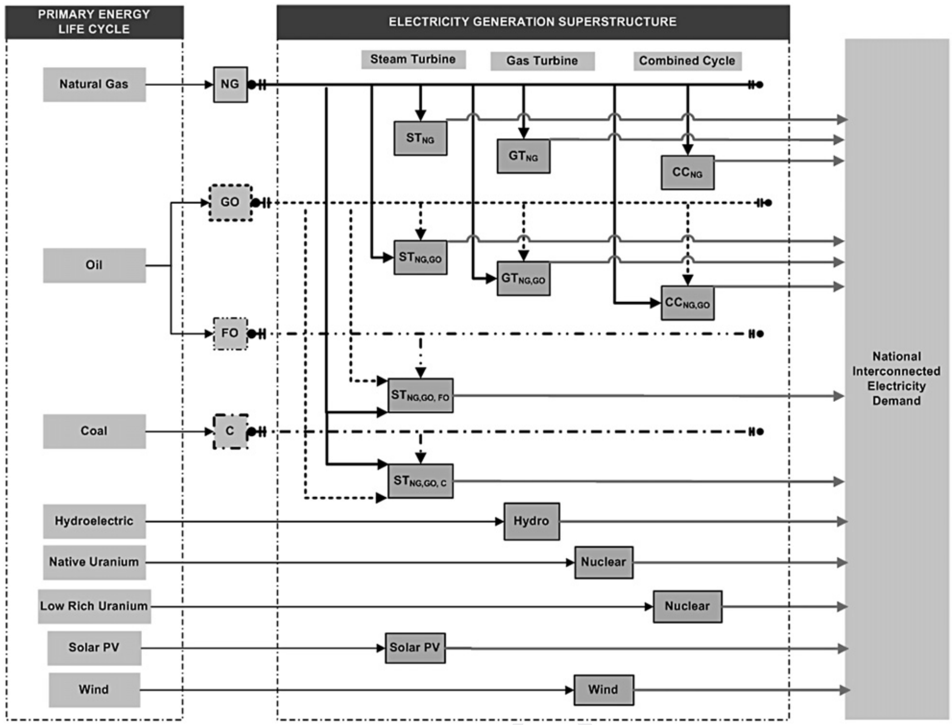

Fig. 1 – Electricity generation network superstructure.

renewable source power plants are ON or OFF during the operation. The electricity generated by any power plant could not be greater than its installed capacity and it cannot be lesser than a certain value imposed by the interconnected system operation:

$$G(q,f) \le G^{Max}(q,f) \times \sum_{f} y_{q,f} \quad \forall q \in F \tag{4}$$

$$G(q) \le G^{Max}(q) \times y_q \quad \forall q \in NF \tag{5}$$

$$d(q,f) \ge d^{LB}_{q,f} \times y_{q,f} \quad \forall q \in F \tag{6}$$

$$d(q) \ge d^{LB}_{q} \times y_q \quad \forall q \in NF \tag{7}$$

Equations (4) and (5) represent upper bounds on electricity production from each plant q. Equation (4) ensures that electricity generation from power plant q is zero when no fossil fuel is assigned and the plant is shut down. Equation (5) indicates that electricity production in non-fossil fuel (NF) plant q is smaller or equal to its maximum capacity. Equations (6) and (7) set up the lower limits in the availability factors of each group of power plants. These lower limits establish the minimum quantity of electricity generated by a certain power plant q.

An upper limit on the availability factor is set up in the Equations (8) and (9), as follows:

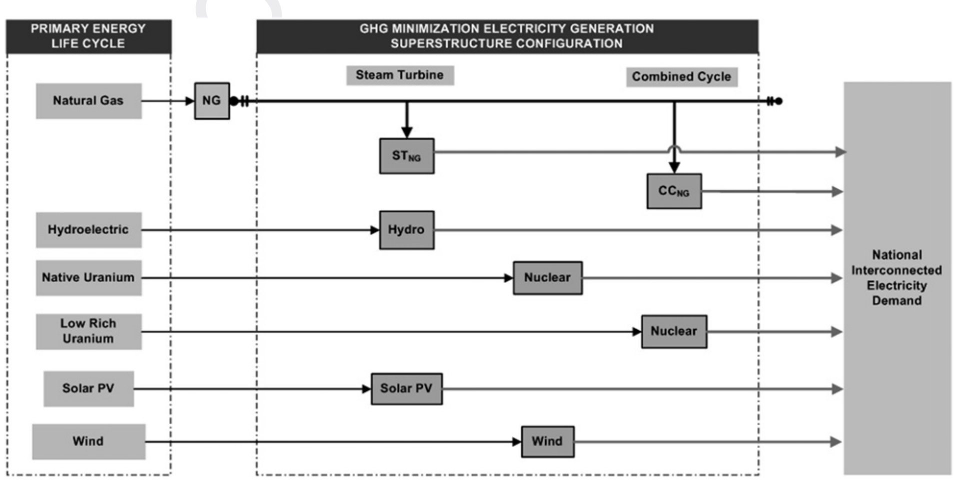

Fig. 2 – Minimum life cycle GHG emissions configuration.

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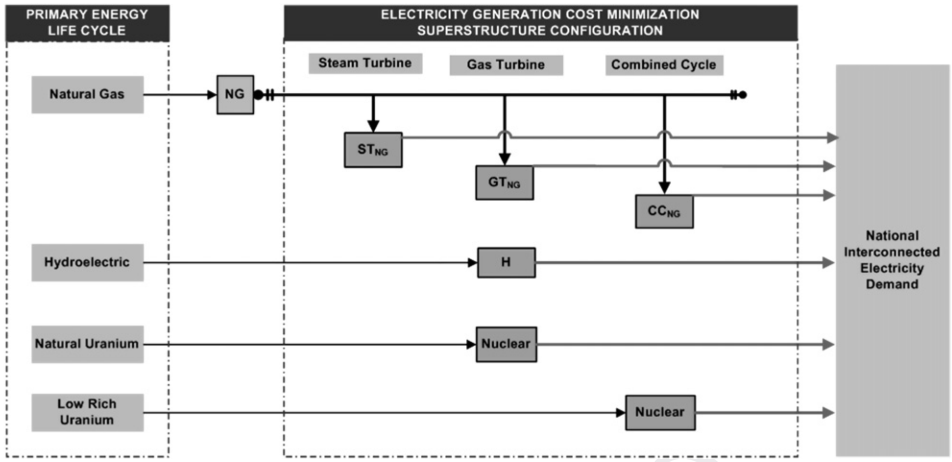

Fig. 3 – Minimum operating cost configuration.

$$d(q,f) \le (1+\beta_q) \times d^a(q,f) \quad \forall q \in F \tag{8}$$

$$d(q) \le (1+\beta_q) \times d^a(q) \quad \forall q \in NF \tag{9}$$

The superscript "a" indicates the current value of the availability factor for each power plant. The parameter β_q is the maximum increment allowed for the availability factor for each power plant in the time period considered. This limit is imposed by the system because of operational constraints as electricity flow transport limits.

A demand satisfaction constraint is shown in Equation (10), where D is the entire network electricity demand for the time period considered:

$$\sum_{q \in F} \sum_{f} G(q,f) + \sum_{q \in NF} G(q) \ge D \tag{10}$$

The operating cost equation for the entire network follows, where $C_F(q,f)$ and $C_{NF}(q)$ are the operating cost of each power plant in US$/Gwh, including fuels and maintenance costs.

$$C_G = \sum_{q \in F} \sum_{f} G(q,f) \times C_{G,F}(q,f) + \sum_{q \in NF} G(q) \times C_{G,NF}(q) \tag{11}$$

The superstructure containing all possible configurations with the available generation units is shown in the following figure.

In Fig. 1, ST stands for Steam turbine, GT for Gas turbine and CC for Combined cycle power plant technology. The following acronyms are used to denote the fossil fuel used: C for coal, NG for natural gas, FO for fuel oil and GO for gas oil. The acronym PV indicates photovoltaic. Additional technologies for electricity generation could be included in the superstructure.

3. Life cycle greenhouse gas emissions quantification

A life cycle approach is used to estimate GHG emissions of each electricity generation technology. The life cycle approach considers emissions during the life cycle of each electricity generation plant, from raw material extraction to waste disposal including the generation step itself. The quantification of GHG emissions is estimated using emission factors, which express the mass of a certain greenhouse gas k emitted by unit of electricity power generated. Greenhouse gases include CO_2, N_2O, CH_4, SF_6 and CFCs, each of them having different heat-trapping properties. To compare their effects on the atmosphere the Global warming potentials (gwp) are used. Global warming potential express the ability of a greenhouse gas to trap heat in the atmosphere relative to an equal amount of carbon dioxide, thus a gwp factor is expressed in mass of CO_2 equivalent/mass of GHG k. Hence, to obtain the amount of GHG emissions CO_{2e} (mass of carbon dioxide equivalent), the mass of greenhouse gas k (CO_2, CH_4, N_2O) is multiplied by its corresponding gwp_k factor (1, 21, 310 respectively) taken from the work by Guinée et al. [14]. According to Dones et al. [15] emissions of SF_6 and CFCs are negligible in fossil fuel combustion and during electricity life cycle, thus they were not considered in the present work. Therefore, the life cycle GHG emissions for the entire network are calculated as follows:

$$F^{LC}_{GHG} = \sum_{q \in F} \sum_{f} \sum_{l} G(q,f) \times E^{l}_{GHG}(q,f) + \sum_{q \in NF} \sum_{l} G(q) \times E^{l}_{GHG}(q) \quad l = 1, \ldots, l_q \tag{12}$$

$$E^{l}_{GHG}(q,f) = \sum_{k} E^{l}_{k}(q,f) \times gwp_k \tag{13}$$

$$E^{l}_{GHG}(q) = \sum_{k} E^{l}_{k}(q) \times gwp_k \tag{14}$$

Where E^l_k is the emission factor of greenhouse gas k in the life cycle stage l expressed in tons of CO_{2e}/Gwh. The subscript GHG indicates the summation over the three greenhouse gases considered in each life cycle stage l.

Life cycle stages, l_q considered for each power generation technology are described in the following section.

3.1. *Thermoelectric power generation*

GHG emissions are estimated in the following life cycle stages: (i) generation step of each thermoelectric option and (ii) fossil fuels life cycle. Pollutant emissions in the electricity generation step are dependant of the specific thermal power plant technology and the fossil fuel used as thermal energy source. Thermal power plant technology includes steam turbines (ST), gas turbines (GT) and a combination of both, the combined cycle (CC) technology. Steam turbine technology uses steam as work fluid, so it is needed to generate steam as a first step, and then this steam is used to drive the turbine. In the case of gas turbine, the work fluid is the combustion gas stream that passes through the turbine generating shaft work; the remaining hot gas stream is not further used and finally released. A combined cycle power plant takes advantage of both kinds of turbines. First, combustion gases drive the gas turbine unit and the exhausted gases are then used to generate steam that in turn drives the steam turbine unit. The range of electric-thermal efficiency is between 0.25 and 0.30 for gas turbine power plants, 0.30 to 0.45 for steam turbine and 0.45–0.55 for combined cycle power plants [16]. In terms of emission rates, not only the power plant efficiency is an important parameter but the fossil fuel aggregation state and quality are key variables. Gas fuels are less pollutant than liquid fuels, which in turn are less pollutant than solid fuels. Quality of the fuel, particularly the carbon content determines the CO_2 emission rate.

On the other hand, fuel life cycle emissions evaluation considers the upstream process needed to produce fossil fuels burnt in the generation step. Exploration, extraction, transport and refining stages are considered for fuel oil and gas oil. Extraction and transport stages are considered for coal. For natural gas, extraction/production, refining and transportation stages are considered. Emissions due to natural gas leakage in extraction and transportation stages, which reflects the system actual behavior, are also considered. Emission factors published by the US-EPA [17] were used in each generation step. The emission factors for each fuel life cycle step are taken from the AEA report [18].

3.2. *Hydroelectric power generation*

Hydropower's air emissions are negligible because no fuels are burned; however pollutants emissions, especially GHG are released during the construction and operational stages of a hydroelectric power plant. These emissions come from the dam construction and the biomass decay. According to Gagnon and van de Vate [19] and the International Energy Agency, IEA [20], in the dam, dikes and power station construction stage, a huge amount of material is transported in trucks with internal combustion engines that emit greenhouse gases. Pollutant emissions during the operational stage of a hydroelectric power plant come from the flooded biomass decay. The biomass decomposition could be produced in aerobic or anaerobic conditions and both of them are usually produced at the same time. As it was stated by Gagnon et al. [21] GHG emissions could be present 20 years after the land flooding. Aerobic decomposition of organic matter generates CO_2 and H_2O, in the other hand anaerobic decomposition of biomass also generates CH_4, and in a lesser extent N_2O and NO_x. Pollutant emission rates depend on specific parameters as the flooded area and quantity and diversity of flooded biomass, these parameters are dependant on the ecosystem where the water reservoir is located. Geographical location of the reservoir will affect the water temperature and consequently the biomass decomposition rate. Duchemin et al. [22] had registered GHG emission rates of 10–60 g CO_{2e}/Kwh for reservoirs located at template and arid lands, in the other hand Pinguelli et al. [23] had reported values of 340–360 g CO_{2e}/Kwh for tropical forest hydroelectric power plants in Brazil.

3.3. *Nuclear power generation*

Nuclear power plants do not emit CO_2 or any GHG; the power plant emissions during the energy production are mainly aqueous ones as chlorides, ammonia and ion metals, (AEA report [18]). However GHG emissions are associated with the uranium fuel life cycle and nuclear power plant construction. The nuclear fuel cycle may be broken down in the following stages: uranium mining, milling, conversion, enrichment, fuel rods fabrication, spent fuel reprocessing and waste disposal.

The uranium mining and milling stages produce CO_2 (and other greenhouse gases) emissions because of transportation of uranium ore in trucks. In the fuel fabrication stage, a special mineral ore is transformed into solid pellets of uranium; this process is electricity consuming one. Spent fuel reprocessing and waste disposal stages are also electricity dependant stages but with a few data available in scientific literature. An additional life cycle stage considered in nuclear energy production is the power plant construction stage. During the power plant construction, there are some greenhouse emissions when building materials are transported in trucks.

3.4. *Solar and wind electricity generation*

The life cycle GHG emissions of solar photovoltaic and wind electricity generation include those arising from the fabrication of the generation unit, the erection of the integrated system and the operation.

3.4.1. *Solar photovoltaic*

A solar photovoltaic electricity system includes the photovoltaic modules, power electronic devices and supporting structure. The power electronic is needed to convert direct current to alternating current. For a solar photovoltaic grid-connected system no batteries are needed, Zhai and Williams [24]. Solar photovoltaic system life cycle includes the following stages mineral silica extraction, silica to silicon transformation, mineral silicon to solar silicon grade transformation process and photovoltaic panel assembling. Glass, aluminum and copper are also needed for the solar photovoltaic power plant mounting.

As it was reported by Stopatto [25], the most GHG intensive stages are the transformation of metallic silicon into solar grade silicon and the panel assembling, due to the great electricity consumption of these processes.

3.4.2. *Wind electricity*

A wind farm includes the wind towers itself, the power electronics and the farm infrastructure. A wind turbine consists of many electrical, electronic and mechanical components been the base, the tower, the nacelle and the rotor the main parts, Martínez et al. [26]. Foundations are made by concrete, iron and steel bars. The tower is made of steel, the rotor (usually three blades) are made by fiber glass and resin; finally the nacelle consist of many sub-components and electrical parts. Inside the nacelle are the components of the turbine used to convert the mechanical rotational energy of the rotor into electrical power, the main components are the shaft, the gearbox, the generator and the transformer been copper, iron and steel the main materials involved in its construction. So, the stages involved in wind power generation include iron and copper extraction and the production of steel, resins, fiber glass and concrete.

The GHG emission factors for these two renewable electricity sources was adapted from data presented by Evans et al. [27] which include an extensive literature review of solar photovoltaic and wind turbine fabrication processes considering the life cycle stages previously described.

4. Argentinean interconnected electricity network

The Argentinean electricity network is composed by fifty one thermoelectric power plants consuming four alternative different fossil fuels (NG, FO, GO and C), forty hydroelectric power stations, two nuclear power plants (NPP) and two renewable source power plants.

4.1. *Thermoelectric power sector*

The fifty one thermoelectric power plants have 182 thermal machines including gas and steam turbines and combined cycle units. A small quantity of electricity from biomass (mainly wood and bagasse) is produced in the northern provinces of Argentina; however this electricity production is not delivered to the national interconnected system but it is used in the sugar cane industry. Natural gas is widely used in the thermoelectric power generation sector accounting for 79% in year 2007. Electricity generation technologies as well as fuels used for the thermoelectric power sector of the Argentinean electricity system are presented in Table 1.

Ninety nine thermal machines were not used in 2007 because technical and economic reasons been the total installed capacity of the thermoelectric power generation sector in 2007 equal to 13449, 230 MW (data from the 2007 National Electric Sector Report [28]).

Table 1 – Thermoelectric plants of the Argentinean electricity network.

Generation technology	Fixed fossil fuel				Alternative fossil fuels		
	NG	FO	GO	C	NG/GO	NG/FO	NG/FO/C
Steam turbine	18	–	15	–	–	30	3
Gas turbine	46	–	–	–	47	–	–
Combined cycle	15	–	–	–	13	–	–
Total	79	–	15	–	55	30	3

4.2. *Hydroelectric power sector*

Argentina has forty hydroelectric power stations with an installed capacity per power central ranging from a few kilowatts to hundreds of megawatts. There are two major hydroelectric zones in the country both located in very different ecosystems, subtropical plane and the semiarid environment. Located in the first zone are two big hydroelectric power plants accounting for 27% of the country hydroelectric installed capacity. In the second ecosystem there are a series of 7 dams in two rivers which accounts for 47% of the total hydroelectric installed capacity (e.g. The Comahue Basin in Patagonia geographical region). Finally, the remaining 26% is located all around the country and it is considered in the semiarid ecosystem zone [28]. In summary, the emission factor for the generation step due to biomass decay is a weighted sum of the emission factor for subtropical ecosystems reported by Pinguelli et al. [23] and the corresponding emission factor for semiarid ecosystems reported by Duchemin et al. [22].

4.3. *Nuclear power sector*

There are two operating nuclear power plants in Argentina, Embalse NPP and Atucha I NPP. There is a third NPP that is going to be commercially available next year. Embalse NPP uses CANDU (Canadian Deuterium-Uranium reactor) technology as nuclear power reactor. This kind of nuclear reactor consumes native uranium as fissile fuel and heavy water as moderator and refrigerator fluid. Native uranium is the mineral ore with the natural content of the fissile isotope ^{235}U. Atucha I NPP has the same reactor technology but it consumes a mix fuel composed by native and low rich uranium. Low rich uranium (LRU) is that fuel with a major quantity of the uranium fissile isotope produced through a separation process based on the atomic mass difference between the uranium isotopes. Both native and LRU are not produced in the country besides they are imported from Brazil and the fuel bars are produced in Argentina. Then, different life cycle stages have to be considered for each of the uranium fuels. For native uranium, enrichment stage is not considered but it does for the LRU fuel used at Atucha I NPP. The total installed capacity of the nuclear power sector in Argentina is 1026 Mw [28].

4.4. *Renewable electricity power sector*

The current development of the renewable electricity generation sector is in it very beginnings in Argentina. The first wind farm started to operate in 1994 and the first photovoltaic electricity plant started in the first part of year 2011. The current installed capacity in wind farms is 29.8 MW in fourteen wind farms all around the country, with a special widespread in Patagonia Region. Unfortunately this installed capacity is still not connected to the national electricity grid due to some technical and regulatory issues. Just 2.4 MW out of the total installed capacity had been recently connected to the grid. The rest of installed capacities are small wind farms belonging to local electricity cooperatives in small towns.

The solar photovoltaic electricity plant is currently in its starting phase and it was designed to directly deliver electricity to the national interconnected system, its installed capacity is 1.2 MW and uses three different kind of photovoltaic panel technology (polycrystalline, mono-crystalline and amorphous, according to electricity national company report, CAMMESA [29]).

4.5. *Overall national interconnected system*

Data of system operation and installed capacity, availability factors bounds, power plant efficiencies and generation costs were taken from the electricity national company report, CAMMESA [29]. The power demand for year 2007 was equal to 102,158.87 GWh and it was formulated as an inequality constraint, being active at the solution point. The initial point of the optimization problem corresponds to the operating conditions of year 2007. The electricity generation in 2007 had the following distribution: 62.95% Thermoelectric, 29.98% Hydroelectric and 7.07% Nuclear. Data of installed capacity and plant efficiency for the renewable electricity sector was taken from the Argentine Renewable Energy Association [30].

Fuel desegregation for the thermoelectric power subsystem, year 2007, is presented in Table 2; where generated electricity is presented in GWh and the number of thermal machines is presented in braces.

5. Selection of the operating conditions of the electricity network

The configuration and loads of the power plants of the Argentinean interconnected electricity system were selected minimizing life cycle GHG emissions and generation cost, respectively. Mixed integer linear programming (MILP) problems are formulated and solved in GAMS [12]. The selection of the operating conditions of the national interconnected electricity system for a given demand are carried out minimizing life cycle GHG emissions and operating cost separately as follows.

5.1. *Life cycle GHG emissions minimization*

The selection of the electricity generation units in operation and their optimal loads minimizing life cycle GHG emissions of the Argentinean interconnected electricity network was carried out solving problem P1 in GAMS [12], using the code CPLEX to solve the MILP problem.

5.1.1. *Environmental optimization problem*

$$\begin{aligned} \min_{x,\,y} \quad & F^{LC}_{GHG}(x,\,y) \\ \text{s.t.} \quad & \\ & A.x = 0 \\ & B.x + C.y \le 0 \\ & x \in R^n \\ & y \in \{0,\,1\} \end{aligned} \tag{P1}$$

The objective function in problem P1 is the sum of life cycle GHG emissions of the entire electricity system as it was stated in Equation (12), with life cycle GHG emission factors given in Equations (13) and (14). Variables x and y are the continuous and binary optimization variables respectively. Continuous optimization variables are the availability factors for each power generation plant. Equality constraints represent the generation model given in Equations (1) and (2). Inequality linear constraints are included to represent minimum and maximum plant capacity, maximum fuel availability, electricity demand satisfaction and bounds on continuous variables, Equations (3)–(10). Continuous optimization variables are the availability factors for all the power generation plants.

The optimization problem has 8600 equations, including equality and inequality constraints, 6559 continuous variables corresponding to the operating loads of each electric power machine and 1836 binary variables corresponding to the selection of the power plants in operation in the interconnected system and the alternative fossil fuel (NG, FO, GO or C) used in the corresponding thermoelectric power plants.

The environmental optimization problem P1 was solved in 0.078 s and 93 iterations of the CPLEX solver. The main results are shown in Table 3. The results minimizing life cycle GHG emissions of year 2007 (solution point minimizingF^{LC}_{GHG}) are shown together with the operation of year 2007. Significant reductions of 34% and 52% in GHG emissions and operating cost respectively, are achieved by properly selecting the configuration and loads of the electricity generation plants. Thermoelectric generation was reduced, while hydroelectric, nuclear and alternatives (e.g. wind and solar photovoltaic) generations were increased. The more efficient and less pollutant thermoelectric plants were selected, such as the combined cycle and steam turbines thermoelectric plants burning NG. Hydroelectric and nuclear

Table 2 – Fossil fuel desegregation for thermoelectric generation. Q3

Thermoelectric generation technology	Fossil fuel				
	Natural gas	Fuel oil	Gas oil	Coal	Total
Combined cycle	6218.527 [5]	–	1356.181 [1]	–	7574.708
Steam turbine	11861.408 [13]	8354.342 [11]	–	1529.120 [1]	21,744.87
Gas turbine	32685.743 [49]	–	2300.056 [3]	–	34,985.799
Total	50765.678 [67]	8354.342 [11]	3656.237 [4]	1529.120 [1]	64,305.378
%	78.945	12.992	5.686	2.378	100

Table 3 – Improvements achieved minimizing GHG emissions.

		Year 2007	Min F^{LC}_{GHG}	% reduction
GHG emissions	10^6 tons CO_{2e}	43.724	28.742	34.25
Operating cost	10^6 US$	1175.617	560.165	52.35
Thermoelectric CC	Gwh/plants	7574.709/6	43,572.597/20	−82.62
Thermoelectric ST	Gwh/plants	21,744.870/25	15,541.816/10	28.57
Thermoelectric GT	Gwh/plants	34,985.799/52	–	100
Total thermoelectric	Gwh/plants	64,305.378/83	59,114.413/30	8.07
Hydroelectric	Gwh/plants	30,636.264/25	35,019.137/40	−12.51
Nuclear	Gwh/plants	7217.228/2	8015.600/2	−9.96
Wind	Gwh/plants	0.00/0	8.131/1	−100
Solar PV	Gwh/plants	0.00/0	1.584/1	−100
Total electricity generation	Gwh/plants	102,158.87/110	102,158.865/74	0.00

are also the cheapest options. The thermoelectric units burning the most expensive and pollutant fuels such as FO, GO and C were shut down. Due to its very low GHG emission rate, wind and solar photovoltaic electricity plants are also selected at the solution point. The following figure shows the configuration achieved minimizing the life cycle GHG emissions of the superstructure.

At minimum life cycle GHG emissions only thermoelectric power plants burning NG were selected while FO, GO and C machines were not selected, however in year 2007 these fuels were actually used to generate electricity [28,29].

The CO_2 emission rate for a given power generation technology is proportional to its power generation electrical efficiency and its specific fuel consumption rate. So, when CO_2 emissions are minimized, only the less pollutant technologies are selected, those technologies are also the most efficient. Less pollutant technologies are those burning the less carbon intensive fuel as NG and the most efficient are those that convert as much as possible the energy content of the fuel into electricity output, as it is the case of combined cycle units and steam turbine units. Gas turbines have the smallest electrical efficiency and are not longer selected to minimize GHG emissions at the solution point. Alternative electricity generation options are also selected at the solution point. Less pollutant electricity generation technologies as wind, solar photovoltaic, hydroelectric and nuclear are selected to minimize life cycle GHG emissions.

5.2. *Interconnected system generation cost minimization*

The selection of the generation units and their optimal loads to minimize the generation cost of the Argentinean interconnected electricity network was carried out solving problem P2 in GAMS [12], using the code CPLEX to solve the MILP problem.

5.2.2. *Economical optimization problem*

$$
\begin{aligned}
&\min_{x,\,y} \quad C_G(x,\ y) \\
&\quad \text{s.t.} \\
&\qquad A.x = 0 \\
&\qquad B.x + C.y \le 0 \\
&\qquad x \in R^n \\
&\qquad y \in \{0,\ 1\}
\end{aligned}
$$

The objective function in problem P2 is the electricity generation cost of the interconnected system given in Equation (11). As in the environmental problem formulation, x and y are the continuous and binary optimization variables respectively. Continuous optimization variables are the availability factors for all the power generation plants. Equality constraints represent the generation model given in Equations (1) and (2). Inequality linear constraints are included to represent minimum and maximum plant capacity, maximum fuel availability, electricity demand satisfaction and bounds on continuous variables, Equations (3)–(10). The problem was solved in 0.078 s and 79 iterations of the CPLEX solver. The main improvements achieved minimizing the operating cost with respect to operation of the electricity network in year 2007 are reported in Table 4.

At the solution point only thermoelectric power plants burning NG were selected while FO, GO or C machines were not selected. Natural gas is the cheaper fossil fuel in the current Argentinean fuel market; this fact explains why other fossil fuels are not selected when minimizing operating cost. The combined cycle units have increased significantly with respect to the initial point, because combined cycle units have the biggest efficiency value of the overall thermoelectric subsystem. The configuration obtained minimizing the generation cost of the electricity generation superstructure is presented in Fig. 3: Q2

Constraints reinforcing national regulations, related to the use of certain fuels like coal in order to keep employment in mining areas, could be added to the problem formulation and would reduce the improvement reported. The versatility of the model presented in this work, also gives the possibility to include environmental constraints as emission reduction targets on units, sectors or even the whole system.

Fuel availability and hydroelectric seasonal variation could also be considered and included as constraints, in different scenarios. It is also important to note that the Argentinean electricity sector is experiencing a diversification of the electricity generation matrix increasing the participation of renewable energy sources encouraged by governmental policies, Recalde and Guzowski [31]. The National Program on Renewable Energies [32] is considering a contribution of 8% in renewable electricity generation by 2020. The model presented could also be extended to include bio-fuel based technologies, without major changes in the mathematical formulation.

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Table 4 – Improvements achieved minimizing operating cost.

		Year 2007	Min C_G	% reduction
GHG emissions	10^6 tons CO_{2e}	43.724	30.768	29.63
Operating cost	10^6 US$	1175.617	536.705	54.35
Thermoelectric CC	Gwh/plants	7574.709/6	44,762.997/24	−83.08
Thermoelectric ST	Gwh/plants	21,744.870/25	12,745.451/8	41.39
Thermoelectric GT	Gwh/plants	34,985.799/52	1615.680/4	95.38
Total thermoelectric	Gwh/plants	64,305.378/83	59,124.128/36	8.06
Hydroelectric	Gwh/plants	30,636.264/25	35,019.137/40	−12.51
Nuclear	Gwh/plants	7217.228/2	8015.600/2	−9.96
Wind	Gwh/plants	–	–	–
Solar PV	Gwh/plants	–	–	–
Total electricity generation	Gwh/plants	102,158.865/110	102,158.865/78	0.00

The operation minimizing the generation cost shows life cycle GHG emissions which are 9.82% bigger than the life cycle GHG emissions at their minimum value. On the other hand, the minimization of life cycle GHG emissions has a generation cost which is 3.87% bigger than the minimum generation cost. Forty hydroelectric and two nuclear power plants are in operation in both cases. Wind and solar photovoltaic are selected only when minimizing life cycle GHG emissions due to their high operational cost. The following distribution is held: thermoelectric generation is equal to 59,124.128 GWh (57.87%), hydroelectric generation is equal to 35,019.137 GWh (34.28%) and nuclear generation is equal to 8015.600 GWh (7.85%), except for the operation at minimum GHG emissions where a contribution of 0.008% for wind and 0.002% for solar photovoltaic is reached.

6. Conclusions

A methodology to optimally select the configuration and unit operating loads of an interconnected national electricity network was presented. Mixed integer linear programming problems were formulated to minimize life cycle GHG emissions and operating cost. Significant reductions in both objectives are achieved. MILP problems were formulated and solved in GAMS, with the solver CPLEX. As a general trend, hydroelectric, nuclear and the most efficient and less pollutant thermoelectric units as combined cycle burning natural gas, are in operation. While less efficient thermoelectric power plants burning coal, fuel oil and gas oil are shut down. Hydroelectric, nuclear and combined cycle thermal units burning natural gas are also the cheapest options.

REFERENCES

[1] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007;32: 1553–9.
[2] Hashim H, Douglas P, Elkamel A, Croiset E. Optimization model for energy planing with CO_2 emission consideration. Industrial and Engineering Chemical Research 2005;44: 879–90.
[3] El-Halwagi M, Santibañez-Aguilar J, González-Campos B, Ponce-Ortega J, Serna-González M. Optimal planning of a biomass conversion system considering economic and environmental aspects. Industrial and Engineering Chemical Research 2011;50:8558–70.
[4] Elkamel A, Mirzaesmaeeli H, Douglas P, Croiset E, Gupta M. A multi-period optimization model for energy planning with CO_2 emission consideration. Journal of Environmental Management 2010;91:1063–70.
[5] Ren H, Zhou W, Nakagami K, Gao W, Wu Q. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Applied Energy 2010;87:3642–51.
[6] Dincer I, Granovskii M, Rosen M. Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: economic Factors. International Journal of Hydrogen Energy 2007;32:927–31.
[7] Eliceche AM, Martínez P. Recycling a hydrogen rich residual stream to the power and steam plant. International Journal of Hydrogen Energy 2010;35:5882–9.
[8] Eliceche A, Corvalan S, Martinez P. Environmental life cycle impact as a tool for process optimization of a utility plant. Computers and Chemical Engineering 2007;31:648–56.
[9] Martínez P, Eliceche A. Bi-objective minimization of environmental impact and cost in utility plants. Computers and Chemical Engineering 2011;35:1478–87.
[10] Pasquevich D, Dawidowski L, Gómez D, Martínez P. Life cycle greenhouse emissions of compressed natural gas-hydrogen mixtures for transportation in Argentina. International Journal of Hydrogen Energy 2010;35:5793–8.
[11] Martínez P, Eliceche A. Minimization of life cycle CO_2 emissions in steam and power plants. Clean Technologies and Environmental Policy 2009;11(1):49–57.
[12] Brooke A, Kendrick D, Meeraus A, Raman R, editors. GAMS, a user guide. Washington DC: GAMS Development Corporation; 2003.
[13] Martínez P. Life cycle assessment as a tool for process optimization. PhD thesis. Bahía Blanca, Argentina: Universidad Nacional del Sur; 2008.
[14] Guinée J, Heijungs R, Huppes G, Kleijn R, Koning A, van Oers L, et al., editors. Handbook on life cycle assessment. Operational guide to the ISO standards. Dordrecht: Kluwer Academic Publishers; 2002.
[15] Dones R, Heck T, Hirschberg S. Greenhouse gas emissions from energy systems, comparison and overview. Encyclopedia Energy 2004;3:77–95.
[16] Elliot TC. Standard handbook of power plant engineering. New York: Mc Graw Hill; 1989.
[17] U.S. EPA. Environmental Protection Agency. AP-42 compilation of air pollutant emission factors; 1998.
[18] AEA Technology Environment. Power generation and the environment – a UK perspective, vol. 1; 1998. Oxfordshire.

[19] Gagnon L, van de Vate J. Greenhouse gas emissions from hydropower. Energy Policy 1997;25(1):7–13.

[20] IEA. International Energy Agency. Hydropower and the environment: present context and guidelines for future action, vol. II. Oslo: Main Report; 2000.

[21] Gagnon L, Bélanger C, Uchiyama Y. Life-cycle assessment of electricity options: the status of research in year 2001. Energy Policy 2002;30:1267–78.

[22] Duchemin E, Lucotte M, St-Louis V, Canuel R. Hydroelectric reservoirs as an anthropogenic source of greenhouse gases. World Resource Review 2002;14(3):334–53.

[23] Pinguelli L, dos Santos A, Matvienko E, Sikar E. In: Coimbra Alberto Luis, editor. Carbon dioxide and methane emissions from Brazilian hydroelectric reservoirs. First Brazilian inventory of anthropogenic greenhouse gas emissions, background reports. Brasilia: Institute for Graduate Studies and Research in Engineering, Brazilian Ministry of Science and Technology; 2002.

[24] Zhai P, Williams E. Dynamic hybrid life cycle assessment of energy and carbon multicrystalline silicon photovoltaic systems. Environmental Science and Technology 2010;44: 7950–5.

[25] Stoppato A. Life cycle assessment of photovoltaic electricity generation. Energy 2008;33:224–32.

[26] Martínez E, Sanz F, Pellegrini S, Jíménez E, Blanco J. Life cycle assessment of a multi-megawatt wind turbine. Renewable Energy 2009;34:667–73.

[27] Evans A, Strezov V, Evans T. Assessment of sustainability indicators for renewable energy technologies. Renewable and Sustainable Energy Reviews 2009;13:1082–8.

[28] Informe del sector eléctrico año. Secretaría de Energía de la Republica Argentina. 2008; 2007.

[29] CAMMESA. Compañía Administradora del Mercado Eléctrico Mayorista Sociedad Anonima, Informe Anual 2007. Buenos Aires, 2007.

[30] CADER. Cámara Argentina de Energías Renovables. www.argentinarenovbles.org.

[31] Recalde M, Guzowski C. Renewable energy in Argentina: energy policy analysis and perspectives. International Journal of Hydrogen Energy 2008;33:3592–5.

[32] GENREN-2010. Programa nacional de generación a partir de fuentes renovables de energía. Ministerio de Planificación Federal, Inversión Pública y Servicios de Argentina; 2010.

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