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Operation of the Argentinean Interconnected Electricity Network

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Abstract

A methodology to select optimally the electricity generation plants of the Argentinian interconnected network is developed. The electricity generation grid has different fossil fuel, hydroelectric and nuclear power stations. The power plants configuration connected to the grid and their operating loads are selected minimizing life cycle greenhouse gas emissions and operating cost simultaneously. A life cycle approach to estimate greenhouse gas emissions of thermoelectric, hydroelectric and nuclear power plants is followed. Binary operating variables represent discrete decisions to select which power plant is connected to the grid and the type of fossil fuel used. Continuous operating variables are introduced to select the optimal load for each power plant. A mixed integer linear programming problem is formulated and solved in GAMS. Significant reductions in green house emissions and operating cost are achieved simultaneously in the operation of the electricity network. Thus, a useful tool to support a decision-making process in the operation of a key energy sector is presented.

Keywords: Interconnected electricity network, operation, greenhouse emissions, cost.

1. Introduction

Environmental concerns have reached a high societal interest in a few years. Special interest has received greenhouse emissions of energy generation, claiming for environmental responsible energy policies. The main source of greenhouse emissions is the combustion of fossil fuels although greenhouse emissions are also present in the entire life cycle of many products or services, and electricity is not an exception. The upstream processes include raw material extraction, processing and distribution consuming energy, which have associated greenhouse emissions due to both fossil fuel consumption and fugitive emissions. Weisser (2007) presented an exhaustive work on life cycle greenhouse emissions in energy generation paying special attention to fossil fuel, nuclear and renewable energy technologies in the European Union and Japan. Hashim et al. (2005) studied the Ontario energy system minimizing CO_2 emissions. However, the authors have not considered the life cycle CO_2 emissions occurred in the upstream processes of each electricity generation option. The international price of CO_2 emissions is included in the objective function of the mixed integer linear programming problem formulated.

In the present work, life cycle green house emissions are estimated in the electricity generation and the limits of each power plant are extended, from raw material extraction to waste disposal. The Argentinean electricity grid has coal, fuel oil, gas oil and natural

gas driven thermoelectric plants, nuclear and hydroelectric plants. The Objective function minimized is a combined function that includes the operating cost and the benefits in the emission trade market for reducing the greenhouse life cycle emissions. The greenhouse gases international price was used to translate an environmental burden into an economic value. The network operating cost includes the costs of fuels and maintenance of each plant. Eliceche and Martínez (2007) successfully used a similar approach to select the operating conditions of a steam and power plant minimizing life cycle greenhouse emission of imported electricity and natural gas feedstock.
The methodology presented for the selection of the operating conditions of the Argentinian electricity network leads to significant reductions in operating cost and green house emissions simultaneously.

2. Electricity Network Modeling

2.1. Electricity Generation
The modeling of the interconnected system includes continuous and binary variables. The generation of each power plant is modeled as a fraction of its installed capacity. Binary variables represent discrete decisions and are introduced to select the type of fossil fuel used in a given thermoelectric plant, and to select which power plant (fossil-fuel based or not) is connected to the grid for a fixed yearly demand. The mix of all the electricity generated is injected into the electricity grid. The model considers the electricity generated by a certain power plant as a fraction of its maximum installed capacity, $\mathbf{G^{Max}}$:

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

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

Where **G(q,f)** is the electricity generated, in *Gwh/yr*, by power plant **q** burning fossil fuel **f**. All the fossil fuel driven power plants are included in the group **F**. **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 and hydroelectric power plants are included. The variables **d(q,f)** or **d(q)** are the availability factor of each power plant. It express the ratio between the energy produced by a power plant in a certain 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.
In order to select the fossil fuel used in a certain fossil fuel power plant, it is necessary to include binary variables in the mathematical model. The binary variable $\mathbf{y_{q,f}}$ 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:

$$\sum_{\mathbf{f}} \mathbf{y_{q,f}} \leq 1 \tag{3}$$

Binary variables $\boldsymbol{y_q}$ are defined for the group of non-fossil fuel plants NF, to select which hydroelectric or nuclear power plants are on or off during the operation. The electricity generated for 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:

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

$$\mathbf{G(q) \leq G^{Max}(q) \times y_{q}} \qquad \forall \mathbf{q} \in \mathbf{NF} \tag{5}$$

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

$$\mathbf{d(q) \geq d^{LB}_{q} \times y_{q}} \qquad \forall \mathbf{q} \in \mathbf{NF} \tag{7}$$

Equations 4 and 5 represent upper bounds on energy production from each plant **q**. The Eq. 4 ensures that electricity generation from power plant **q** is zero when no fossil fuel is assigned to the power plant and the plant is shut down. The Eq. 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.

$$\mathbf{d(q,f) \leq (1+\beta_{q}) \times d^{a}(q,f)} \qquad \forall \mathbf{q} \in \mathbf{F} \tag{8}$$

$$\mathbf{d(q) \leq (1+\beta_{q}) \times d^{a}(q)} \qquad \forall \mathbf{q} \in \mathbf{NF} \tag{9}$$

The superscript “**a**” indicates the current value of the availability factor for each power plant. The parameter $\boldsymbol{\beta_q}$ is the maximum increment allowed for the availability factor for each power plant in the time period considered.
A demand satisfaction constraint is shown in Eq. 10, where **D** is the entire network electricity demand for the time period considered:

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

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

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

2.2. Greenhouse Emissions Quantification

A life cycle approach estimates greenhouse gas emissions of each thermoelectric, hydroelectric and nuclear power plant. 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 greenhouse gases emissions (**GHG**) is estimated using emission factors, which express the mass of a certain greenhouse gas **k** emitted by unit of electricity 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 Potential, the **gwp** factors are used. Global Worming Potential express the ability of a greenhouse gas to trap heat in the atmosphere relative to an equal amount of carbon dioxide, thus **gwp** factor is expressed in *mass of* CO_2 *equivalent/mass of GHG* k. Hence, to obtain the amount of greenhouse 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 $\mathbf{gwp_k}$ factor (1, 21, 310, respectively), Guinée et al (2002). The emissions of SF_6 and CFCs are negligible in fossil fuel combustion and during electricity life cycle (Dones et al, 2004), thus they were not considered in the present work. Therefore, the life cycle greenhouse emissions for the entire network are calculated as follows:

$$\mathbf{F_{GHG}^{LC}} = \sum_{q\in F}\sum_{f}\sum_{l} \mathbf{G(q,f)} \times \mathbf{E_{GHG}^{l}(q,f)} + \sum_{q\in NF}\sum_{l} \mathbf{G(q)} \times \mathbf{E_{GHG}^{l}(q)} \qquad \mathbf{l} = 1,\ldots,\mathbf{l_q} \tag{12}$$

$$\mathbf{E_{GHG}^{l}(q,f)} = \sum_{k} \mathbf{E_k^l(q,f)} \times \mathbf{gwp_k} \tag{13}$$

$$\mathbf{E_{GHG}^{l}(q)} = \sum_{k} \mathbf{E_k^l(q)} \times \mathbf{gwp_k} \tag{14}$$

Where $\mathbf{E_k^l}$ is the emission factor of greenhouse gas **k** in the life cycle stage **l** in *ton of* CO_{2e}*/Gwh*. The subscript **GHG** indicates the summation over the three greenhouse gases considered in each life cycle stage **l**. The total number of life cycle stages, $\mathbf{l_q}$ considered are:

i. *Thermoelectric power generation*: exploration, extraction, refining, transport and generation step for four different fuels: natural gas, fuel oil, gas oil and coal.
ii. *Hydroelectric power generation*: material transport in construction and submerged biomass decay in the operation.
iii. *Nuclear power generation*: exploration, extraction, refining, fuel assembly and transport of uranium, waste treatment and disposal of spent fuel, transport in construction phase of the nuclear plant.

A detailed analysis of each life cycle stage considered as well as the literature sources was presented in Eliceche and Martinez (2007).

3. Optimization Problem Formulation

The objective is to determine the optimal configuration and load distribution for all power plants, to provide the electricity demand to the grid minimizing life cycle green house emissions and operating cost simultaneously. A combined objective function includes the operating cost and the benefit for reducing green house emissions. The greenhouse gases international market price $\mathbf{pr}_{GHG}$ (*US\$/ton of* CO_{2e}) was considered to translate an environmental burden into an economic value.

$$\mathbf{EnvEco(x)} = \mathbf{C_G(x,y)} - \left[\mathbf{F_{GHG}^{LC}(x,y)}\Big|_{\mathbf{in}} - \mathbf{F_{GHG}^{LC}(x,y)}\Big|_{\mathbf{o}} \right] \times \mathbf{pr_{GHG}} \tag{15}$$

The benefit (term in brackets) is proportional to the reduction in green house emissions from the initial point (sub index **in**) and the optimal solution (sub index **o**). The constant term corresponding to the initial point life cycle greenhouse emissions is removed from Eq. 15 leading to the objective function named "**EnvEco**" in the following Mixed Integer Linear optimization problem P1:

$$\begin{aligned}
&\min_{\mathbf{x},\mathbf{y}} \quad \mathbf{EnvEco(x,y) = C_G(x,y) + F_{GHG}^{LC}(x,y) \times pr_{GHG}} \\
&\quad \mathbf{s.t.} \\
&\qquad \mathbf{A.x} = 0 \\
&\qquad \mathbf{B.x} + \mathbf{C.y} \leq 0 \\
&\qquad \mathbf{x} \in \mathbf{R^n} \\
&\qquad \mathbf{y} \in \{0,1\}
\end{aligned} \qquad P1$$

Where **x** and **y** are the continuous and discrete optimization variables respectively; equality constraints represent the generation model given in Equations 1 and 2 and the emission model given in Eq. 12 with life cycle emission factors given in Eq. 13 and Eq. 14. Inequality linear constraints are included to represent minimum and maximum plant capacity constraints, demand satisfaction constraint and bounds on continuous variables, Equations 3 to 11. The continuous optimization variables of the problem are the availability factors for all the power generation plant. Fuel resource constraints and mandatory fuel usage can be included as constraints to represent temporal resource availability due to natural gas pipeline capacity and national policies regarding for example the use of coal. It is also possible to include an inequality constraint with a minimum required reduction in total greenhouse emissions to comply with Kyoto protocol (IPCC, 2001) targets stated for a given country or industrial branch. This constraint was not included, because Argentina has no greenhouse emissions reduction targets up to now.

4. Numerical Results

The configuration and loads of the power plants of the Argentinean interconnected electricity system were selected optimally minimizing operating cost and green house emissions as formulated in problem P1. There are 51 thermoelectric power plants consuming 4 alternative different fossil fuels, 41 hydroelectric power stations and 2 nuclear power plants. The 51 thermoelectric power plants have 170 thermoelectric machines including gas and steam turbines and combined cycle units. Data of system operation and installed capacity, availability factors bounds, power plant efficiencies and generation costs were taken from the electricity national company, CAMMESA (2004). The electricity demand for year 2004 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 2004. The optimization problem P1 is a mixed integer linear programming problem (MILP) solved in GAMS (Brooke, 2003), using CPLEX as a MILP solver. The main results comparing the operation of the electricity network in year 2004 (the initial point) and the optimal operating conditions (solution point minimizing EnvEco) are shown in Table 1. An international price of U$S 20/ton CO_{2e} was considered (Point Carbon, 2004).

Significant reductions of 48 % and 44 % in green house emissions and operating cost are reported by properly selecting the configuration and loads of the electricity generator plants. More constraints reinforcing national regulations related to the use of certain fuels like coal in order to keep employment in mining areas, might reduce the improvement reported in this case study.

Thermoelectric generation is reduced, while hydroelectric and nuclear generation is increased. Thermoelectric units that were kept switch on, were those more efficient and less pollutant as it is the case of combined cycle thermoelectric units burning natural

gas. The shut down thermoelectric units were burning fuel oil, gas oil and coal, which are the most expensive and pollutant fossil fuels. Hydroelectric, nuclear and combined cycle burning natural gas are also the cheapest options.
The methodology presented can be extended to different regional applications and time periods.

Table 1. Improvements achieved selecting the power plants in operation.

		Year 2004	Min EnvEco	% Reduction
GHG Emissions	CO_{2e} 10^3 ton	42.00	21.75	48.21
Operating Cost	10^3 US$	2407.67	1353.62	43.77
EnvEco	10^3 US$	3247.69	1788.71	44.92
Thermoelectric	Gwh / plants	42766.00 / 170	38871.16 / 23	9.11
Hydroelectric	Gwh / plants	31827.00 / 41	35019.58 / 40	-10.03
Nuclear	Gwh / plants	7312.90 / 2	8015.16 / 2	- 9.60
Total Electricity Generation	Gwh	81905.90	81905.90	0.00

5. Conclusions

The methodology developed for the selection of the operating conditions of the Argentinian electricity network leads to significant reductions of more than 40 % in operating cost and green house emissions simultaneously. Hydroelectric, nuclear and the most efficient and less pollutant thermoelectric units, as the combined cycle burning natural gas, are in operation while the less efficient thermoelectric power plants burning coal, fuel oil and gas oil are shut down. Hydroelectric, nuclear and combined cycle burning natural gas plants are also the cheapest options. Thus, a useful tool to support a decision-making process in a key energy sector has been presented.

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