

## Minimization of life cycle CO<sub>2</sub> emissions in the utility sector of a petrochemical plant

Pablo E. Martinez and Ana M. Eliceche

Chemical Engineering Department, Universidad Nacional del Sur, PLAPIQUI-  
CONICET

Camino La Carrindanga km 7, 8000 Bahía Blanca, Argentina.

A methodology is presented to minimize the life cycle CO<sub>2</sub> emissions through the selection of the operating conditions of a steam and power generation plant. The battery limits of the utility sector are extended to include the CO<sub>2</sub> emissions of the imported electricity generated by nuclear, hydroelectric and thermoelectric plants. In the life cycle context the CO<sub>2</sub> emissions are estimated in the following stages: (i) generation, (ii) exploration, extraction and transport of natural gas, oil, coal and uranium consumed in utility, thermoelectric and nuclear plants; (iii) transport in the construction stage and (iv) submerged biomass decay in hydroelectric plants.

A Mixed Integer Nonlinear Programming problem is formulated to select the operating conditions of the utility sector of an ethylene plant in GAMS. Significant reductions in the life cycle CO<sub>2</sub> emissions, natural gas consumption and operating cost are achieved simultaneously solving the Mixed Integer Nonlinear Programming problem in GAMS. The main improvements are reported.

### 1. Introduction

This study focuses on life cycle CO<sub>2</sub> emission assessment associated with the combustion of natural and residual gas and also the electricity imported in a steam and power sector of an ethylene plant. The life cycle approach looks at the supply chain from raw material extraction, through transport and production, to use and waste disposal. Fu and Diwekar (2003) have proposed the minimization of cost and greenhouse gas emissions with a multi objective framework for utilities. Hashim et al. (2005) studied the Ontario energy system minimizing CO<sub>2</sub> emissions in a linear programming problem. Life cycle CO<sub>2</sub> emissions have not been used as the objective function in the optimization of the utility plant previously. The main objective of this work is to select the optimal operating conditions of the steam and power generation plant to reduce the life cycle CO<sub>2</sub> emissions. Temperature and pressure of the high, medium and low pressure steam headers and alternative drivers such as steam turbines and electrical motors are optimally selected. While process engineering is normally concerned with the operations within the plant boundaries (battery limits) (1) in Fig. 1, the life cycle thinking considers the material and energy balances in the extended boundary (2) in Fig. 1, so that the limits between the system and the environment need to be defined including the main processes whose emissions should be considered from raw material extraction to final disposal. Then, the limits of the system are extended to include the generation of the imported electricity, as shown in Fig. 1.

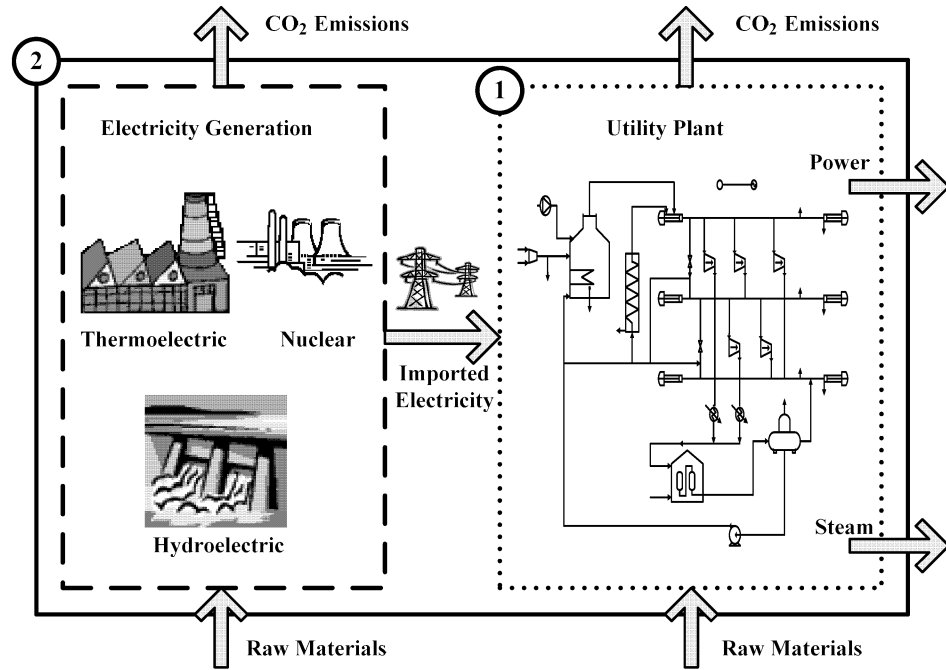


Figure 1. Utility Plant (1) and Imported Electricity Life Cycle (2) boundaries.

The electricity generation sector in Argentina has contributions from thermoelectric, hydroelectric and nuclear plants. Thus the estimation of the CO<sub>2</sub> life cycle emissions in the steam and power plant and electricity generation is described in the following section.

## 2. Estimation of Life Cycle CO<sub>2</sub> Emissions of the Utility Plant

The utility plant provides steam, power and cooling water to the chemical plant. It consumes fossil fuel, a non-renewable resource, burnt in the boilers and a scarce resource as water. The pollution comes mainly from the combustion emissions and the purged water. A schematic flow sheet as well as the extended model of an ethylene plant utility sector is presented in Eliceche et al. (2007).

The utility plant consumes natural gas and the combustion emissions contain pollutants like CO<sub>2</sub>, CO, NO<sub>x</sub>, volatile organic compounds, organic hydrocarbons and trace metals. In this work only the CO<sub>2</sub> emissions are considered. The emissions sources in the natural gas life cycle are mainly the flaring combustion at the gas well and the leakages during transportation. These emissions are estimated from AEA report (1998). Thus the CO<sub>2</sub> emissions for the utility plant, including the natural gas life cycle are estimated as follows:

$$Q_{CO_2}^{UP} = F_{NG} * \sum_l e^l + F_{RG} * e_{RG} \quad , \quad l = 1, \dots, n_l \quad (1)$$

Where  $F_{NG}$  is the natural gas flow rate burned in the boilers and  $e^l$  are the CO<sub>2</sub> emission factors for each life cycle stage  $n_l$ , including combustion in the utility plant and the natural gas fuel cycle (e.g. exploration and transport);  $F_{RG}$  is the residual gas flow rate coming from the top of the demethanizer tower that is burned in the boilers and its corresponding combustion emission factor is  $e_{RG}$ .

The natural gas flowrate is calculated in a rigorous simulation of the utility plant as presented in Eliceche (2007). The emission factor for the generation step are taken from the USEPA AP-42 (1998) report although local information can also be used.

### 3. Estimation of Life Cycle CO<sub>2</sub> emissions of the Imported Electricity

In the electricity generation sector the next fuel cycle stages are considered: exploration, extraction of raw materials, transport, refining, power plant construction and power generation itself. The CO<sub>2</sub> emissions from each life cycle step are modeled using CO<sub>2</sub> emission factors taken from the literature. These emission factors express the mass of CO<sub>2</sub> released by unit of electricity dispatched by each power generation source. The life cycle stages considered in each power source are described in the following section.

#### 3.1 Thermoelectric power generation and fuel life cycle stages

The thermoelectric power sector consumes natural gas, oil, and coal. The generation step is considered for each thermoelectric power option. The Fuel Oil life cycle includes exploration, extraction, transport and refining. For coal and natural gas fuel cycle, extraction and transport stages are considered. In the generation step the emission factor published by USEPA AP-42 (1998) were used. The emission factors for each fuel life cycle step are taken from the AEA report (1998).

#### 3.2 Hydroelectric power generation and life cycle stages

Hydropower's air emissions are negligible because no fuels are burned. Thus the generation step has no associated emissions. On the other hand the hydroelectric power station life cycle has some associated emissions. These emissions come from the dam construction and the biomass decay. In the dam construction stage a huge amount of material is transported in trucks with internal combustion engines that emit greenhouse gases. Gases generated by aerobic and anaerobic decomposition are mainly CO<sub>2</sub>, CH<sub>4</sub>, and to a lesser extent NO<sub>x</sub>, IEA (2000). Therefore, the emission factors reported by IEA (2000) have been used to estimate CO<sub>2</sub> emissions of transport and submerged biomass decay stages.

#### 3.3 Nuclear Power generation and Uranium fuel cycle

Nuclear power plants do not emit CO<sub>2</sub>, the power plant emissions during the energy production are mainly aqueous ones as chlorides, ammonia and ion metals, AEA (1998). However fossil fuel emissions are associated with the fuel life cycle as it is the case of uranium and nuclear plant construction. The nuclear fuel cycle may be broken down in the following stages: uranium mining, milling, conversion, enrichment, fuel fabrication, spent fuel reprocessing and waste disposal. The uranium mining and milling stages produce CO<sub>2</sub> (and other greenhouse gases) emissions because of transportation of uranium mineral in trucks. For fuel fabrication, spent fuel reprocessing and waste

disposal stages there are not available data in the reference. 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 material is transported in trucks.

Therefore, the overall imported electricity CO<sub>2</sub> emission flow rate  $Q_{CO_2}^{IE}$ , is calculated with the following equation:

$$Q_{CO_2}^{IE} = \sum_i (w_i * e_i^{LC}) \quad , \quad i = 1, \dots, n_i \quad (2)$$

Where  $n_i$  has a dimension of seven, representing each electricity generation option  $i$ ;  $w_i$  represents the percentage of electricity imported and  $e_i^{LC}$  represents the life cycle CO<sub>2</sub> emission calculated as follows:

$$e_i^{LC} = \sum_j e_{ij} \quad , \quad j = 1, \dots, n_j \quad (3)$$

Where  $n_j$  represents the total number of life cycle stages  $j$  for each power source  $i$ .

#### 4. Minimization of Life Cycle CO<sub>2</sub> emissions

The overall life cycle CO<sub>2</sub> emission flowrate  $Q_{CO_2}^T$  is calculated adding the life cycle CO<sub>2</sub> emission flowrates from the utility plant  $Q_{CO_2}^{UP}$  and the imported electricity  $Q_{CO_2}^{IE}$ ,

$$Q_{CO_2}^T = Q_{CO_2}^{UP} + Q_{CO_2}^{IE} \quad (4)$$

The following optimization problem is formulated to select the optimal operating conditions of the steam and power plant, minimizing the overall life cycle CO<sub>2</sub> emission flow rate  $Q_{CO_2}^T$  :

$$\begin{aligned} \text{Min}_{x,y} \quad & Q_{CO_2}^T(x,y) \\ \text{s.t. :} \quad & \mathbf{h}(x,y) = \mathbf{0} \\ & \mathbf{g}(x) + \mathbf{A}(y) \leq \mathbf{0} \\ & \mathbf{x}^L \leq \mathbf{x} \leq \mathbf{x}^U \\ & \mathbf{x} \in \mathbf{R}^n \\ & \mathbf{y} \in \{0,1\}^m \end{aligned} \quad (P1)$$

Where  $x$  and  $y$  are the continuous and binary variables. Superscripts U and L indicates upper and lower bounds on vector  $x$ . Pressures and temperatures of high, medium and low-pressure steam headers, deaerator pressure and letdowns are the continuous

optimization variables  $x$ . Integer variables  $y$  allow the selection of alternative pumps drivers such as steam turbines and electrical motors for pumps; they are also used to select whether the boilers and their corresponding air fans are on or off.

The non-linear algebraic equality constraints  $h(x,y) = 0$  represent the steady state modeling of the steam and power generation plant, including mass, energy balances and steam properties prediction. The inequality  $g(x) + A(y) \leq 0$  represent logical constraints, minimum and maximum equipment capacities, operating and design constraints, etc. The  $A$  matrix includes linear functions of the binary variables such as logical constraints.

A detailed model of the steam and power generation plant is presented in a previous paper by Eliceche et al. (2007). The power and steam demands of the ethylene plant are posed as equality constraints. The main power demands correspond to the cracked gas, ethylene and propylene refrigeration compressors. Other power demands correspond to pumps and boiler's air fans.

## 5. Solution of the Mixed Integer Non linear programming Problem

The Electrical Interconnected Network in Argentina has approximately the following distribution: 53% of thermoelectric, 35% of hydroelectric and 12% of nuclear generation. The distribution of thermoelectric generation is: 30% gas turbine, 59% steam turbine burning natural gas, and 11% steam turbine burning oil. There are two nuclear power generation plants using not enriched Argentinean uranium, thus the uranium conversion and enrichment stages have not been considered in the life cycle.

The operating conditions are evaluated minimizing the life cycle  $\text{CO}_2$  emissions in problem P1. There are continuous and binary optimization variables. The continuous variables are temperature and pressure of the high, medium and low steam headers and deaerator tank pressure and letdown flow rates. Binary variables are associated to the selection of pumps drivers such as water tower pumps, lubricating pumps, condensate pumps, boiler water pumps, cooling water pumps and also the boilers and their corresponding air fans. There are twenty four binary variables.

A Mixed Integer Non Linear Programming problem is formulated and solved in GAMS (2003). The MINLP problem was solved with the global optimization solver BARON. The solution was found in 2.50 seconds in a Pentium IV, 3.6 GHz workstation. The main improvements achieved with the selection of the operating conditions solving the optimization problem P1 are presented in Table 1.

Table 1- Improvements achieved minimizing Life cycle  $\text{CO}_2$  emissions

		<b>Initial Point</b>	<b>Optimal Solution</b>	<b>Reduction %</b>
<b>Life Cycle <math>\text{CO}_2</math> Emissions</b>	<b>kg/h</b>	23877.37	22225.49	<b>6.92</b>
<b>Operating cost</b>	<b>\$/h</b>	1855.69	1770.06	4.62
<b>Natural Gas</b>	<b>Tn/h</b>	7.87	7.01	10.84

Temperature and pressure of high, medium and low pressure steam headers are calculated to minimize the CO<sub>2</sub> emissions. The configuration of alternative pumps drivers is chosen with binary optimization variables to select between steam turbines and electrical motors. Binary variables are also used to select which boilers and air fans are on or off. There are four boilers in the utility plant, at the initial point there are three boilers on and at the solution point there are only two boilers on. Less high pressure vapor is generated due to an increment of the efficiency obtained with the selection of the optimal operating conditions requiring only two boilers in operation instead of three. A reduction in the order of 7 % in CO<sub>2</sub> emissions is achieved solving the MINLP problem P1. Simultaneously a reduction of 11% is observed in natural gas consumption, the nonrenewable fossil fuel burned in the boilers, leading to a reduction of 5 % in the operating cost of the utility sector. Thus, minimizing the life cycle CO<sub>2</sub> emissions in the steam and power sector of an ethylene plant has also rendered significant improvement in operating cost and natural gas consumption. These numerical results indicate that the formulation of the optimization problem presented is adequate.

Different formulations of the optimization problem P1 could be implemented, regarding particular scenarios. In future work problem P1 will be reformulated to achieve and specific target of CO<sub>2</sub> emissions reduction, as it would be the case of a particular steam and power plant trying to comply with the Kyoto protocol.

## 6. Conclusions

The methodology presented is an important tool to reduce Carbon Dioxide emissions contributing to the fulfillment of the Kyoto protocol and its emission reduction targets. It is possible to use the plant specific reduction target as a constraint in the optimization problem. This methodology has been applied to a key sector in petrochemical plants obtaining significant reductions not only in Carbon Dioxide emissions but also in natural gas consumption and operating cost. The methodology can be extended to other applications in the energy sector and in process system engineering in general. It is important to extend the battery limits of the process plant to consider the Carbon Dioxide emissions in the context of the environmental life cycle as has been shown in this work.

## 7. References

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