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Minimization of life cycle CO_2 emissions in the operation of a steam and power plant

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Abstract

A methodology is presented to minimize the life cycle CO_2 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_2 emissions of the imported electricity generated by nuclear, hydroelectric and thermoelectric plants. In the life cycle context the CO_2 emissions are estimated in the following stages: (i) exploration, extraction and transport of natural gas, oil, coal and uranium consumed in utility, thermoelectric and nuclear plants; (ii) submerged biomass decay in hydroelectric plants and (iii) transport in the construction stage of hydroelectric and nuclear 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_2 emissions, imported electricity, natural gas consumption and operating cost are achieved and reported in the numerical results.

Keywords: life cycle, CO_2, utility plant.

1. Introduction

This study focuses on life cycle CO_2 emission assessment associated with the combustion of natural gas and 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 [1] have proposed the minimization of cost and greenhouse gas emissions with a multi objective framework for utilities. Hashim et al. [2] studied the Ontario energy system minimizing CO_2 emissions in a linear programming problem. Life cycle assessment was not considered in these previous work. 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_2 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.

The Argentinean electricity generation sector has contributions from thermo electrical, hydro electrical and nuclear plants. Thus the estimation of the CO_2 Life Cycle emissions in the steam and power plant and electricity generation is described in the following section.

2. Estimation of CO_2 Emissions of the Utility Plant Life Cycle

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. [3].

The utility plant consumes natural gas and the combustion emissions contain pollutants like CO_2, CO, NOx, volatile organic compounds, organic hydrocarbons and trace metals. In this work only the CO_2 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 [4]. Thus the CO_2 life cycle emissions are estimated as follows:

$$\mathbf{Q_{CO2}^{UP} = F_{NG} * \sum_{l} e^{l} + F_{RG} * e_{RG}} \tag{1}$$

Where $\mathbf{F_{NG}}$ is the natural gas flow rate burned in the boilers and $\mathbf{e^{l}}$ are the CO_2 emission factors for each life cycle stage l, including combustion in the utility plant and the natural gas fuel cycle; $\mathbf{F_{RG}}$ is the residual gas flow rate coming from the top of the demethanizer tower, burned in the boilers, mainly composed by H_2 and its corresponding combustion emission factor $\mathbf{e_{RG}}$. The natural gas flowrate $\mathbf{F_{NG}}$ is calculated in a rigorous simulation of the utility plant as presented in Eliceche [3]. The emission factor for the generation step are taken from the USEPA AP-42 [5] report although local information can also be used.

3. Electricity generation life cycle models

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_2 emissions from each life cycle step are modeled using CO_2 emission factors taken from the literature. This emission factors express the mass of CO_2 released by unit of electricity dispatched by the power generation source. The life cycle stages considered in each power source are described in the following section.

3.1. Thermo electrical power generation and fuel life cycle stages

The thermo electrical power sector consume natural gas, oil, and coal. The generation step is considered for each thermo electrical 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 [5] were used. The emission factors for each fuel life cycle step are taken from the AEA report [4].

3.2. Hydro electrical power generation and life cycle stages.

Hydropower’s air emission are negligible because no fuels are burned. Thus the generation step has no associated emissions. On the other hand the hydro electrical 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 which emit greenhouse gases. Gases generated by aerobic and anaerobic decomposition are mainly CO_2, CH_4, and to a lesser extent NOx , IEA [6]. Therefore, the emission factors reported by IEA [6] have been used to estimate CO_2 emissions of transport and submerged biomass decay stages.

3.3. Nuclear Power Generation and Uranium fuel cycle

Nuclear power plants do not emit CO_2, the power plant emissions during the energy production are mainly aqueous ones as chlorides, ammonia and ion metals, AEA [4]. 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_2 (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_2 emission flow rate, $\mathbf{Q^{IE}}$, is calculated with the following equation:

$$\mathbf{Q^{IE} = \sum_{s} (w_s * e_s^{LC})} \tag{2}$$

Where $\mathbf{w_s}$ represents the percentedge of energy consumed from the power source **s** and $\mathbf{e_s^{LC}}$ represents the life cycle CO_2 emission factor for the power source **s** calculated as follows:

$$\mathbf{e_s^{LC} = \sum_{l} e_s^{l}} \tag{3}$$

the superscript **l** indicates the life cycle stage considered.

The overall CO_2 flowrate **Q** is calculated adding the life cycle CO_2 flowrates from the utility plant $\mathbf{Q^{UP}}$ and the imported electricity $\mathbf{Q^{IE}}$,

$$\mathbf{Q = Q^{UP} + Q^{IE}} \tag{4}$$

The operating conditions of the utility plant are selected to minimize the overall CO_2 flow rate **Q**.

4. Optimization Problem Formulation

The following optimization problem is formulated to select the operating conditions of the steam and power plant, where the objective function Q is calculated as indicated in Eq. (4):

$$\begin{aligned} &\mathbf{\underset{x,y}{Min}} \quad \mathbf{Q(x,y)} \\ &\mathbf{s.t.:} \quad \mathbf{h(x,y) = 0} \\ &\qquad\quad \mathbf{g(x) + A(y) \le 0} \\ &\qquad\quad \mathbf{x^L \le x \le x^U} \\ &\qquad\quad \mathbf{x \in R^n} \\ &\qquad\quad \mathbf{y \in \{0.1\}^m} \end{aligned} \tag{P1}$$

Where x and y are the continuous and binary variables. Superscripts U and L indicates upper and lower bounds on vector x. 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 relations between binary variables such as logical constraints.

Pressures and temperatures of high, medium and low-pressure steam headers, deaerator pressure and letdowns are the continuous optimization variables.

Integer variables allow the selection of alternative pumps drivers such as steam turbines and electrical motors, and the boilers - air fans. A detailed model of the steam and power generation plant is presented in a previous paper by Eliceche et al. [3]. 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. Numerical results

The Electrical Interconnected Network in Argentina has approximately the following distribution: 53% of thermo electrical, 35% of hydro electrical and 12% of nuclear generation. The distribution of thermoelectric energy 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. Life cycle CO_2 emissions are evaluated for the electricity imported generated in thermo electrical, hydro electrical and nuclear plant and in the steam and power plant as indicated in Eq. (4).

The operating conditions are evaluated minimizing the life cycle 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 air fans.

A Mixed Integer Non Linear Programming problem is formulated and solved in GAMS [7]. The MINLP problem was solved with the code DICOPT, CONOPT++ and CPLEX codes for NLP and MILP sub problems respectively. The solution was found in 5.84 seconds and five major iterations in a Pentium IV, 3.6Ghz workstation. The main results are presented in Table 1.

Significant reductions of more than 10% are achieved in Carbon Dioxide emissions, natural gas consumption, operating cost and water makeup.

Table 1- Main results minimizing the life cycle CO_2 emissions

	Initial Point	Optimal Solution	% Reduction
Life Cycle CO_2 Emissions, kg/h	24798.210	21943.230	11.513
Operating cost, $/h	1963.450	1703.440	13.243
Natural Gas, Tn/h	8.007	7.167	10.485
Make up Water, m3/h	24.753	22.000	11.123
Total HP Steam, Tn/h	184.772	170.300	7.832

Different values of the ratio of Carbon Dioxide emissions to power in the thermo electrical, hydro electrical, nuclear and utility plants provides information to select the drivers configuration to reduce the Carbon Dioxide emissions.

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 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.

References

1. Y. Fu, and U. Diwekar, Advances in Environmental Research, 8 (2003) 173.
2. H. Hashim,P. Douglas, A. Elkamel, E. Croiset, Ind. Eng. Chem. Resources, 44 (2005) 879.
3. A. Eliceche, S. Corvalan, P. Martinez, Comp. and Chem. Eng. (2006), doi:10.1016/j.compchemeng.2006.09.005
4. AEA Technology Environment, Power generation and the environment – A UK perspective, Vol 1, Oxfordshire, 1998.
5. U.S. Environmental Protection Agency, AP-42 Compilation of air pollutant emission factors, fifth edition, North Carolina, 1998.
6. International Energy Agency, Hydropower and the environment: present context and guidelines for future action, Volume II: Main Report, Oslo, 2000.
7. A. Brooke, D. Kendrick, A. Meeraus, R. Raman (eds.), GAMS, A user guide, GAMS Development Corporation, Washington DC, 2003.