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ORIGINAL PAPER

Minimization of life cycle CO_2 emissions in steam and power plants

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Abstract A methodology is presented to minimize 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 plant are extended to include CO_2 emissions of: (1) extraction and transport of natural gas burned in its boilers, (2) generation of imported electricity by nuclear, hydroelectric and thermoelectric plants and (3) exploration, extraction and transport of natural gas, oil, coal and uranium consumed by thermoelectric and nuclear plants. The operating conditions of the utility plant are selected optimally to minimize the life cycle CO_2 emissions. There are continuous operating conditions such as temperature and pressure of the high, medium and low pressure steam headers and binary operating conditions to represent discrete decisions to select optional pumps drivers between electrical motors and steam turbines or whether some equipment is on or off. A Mixed Integer Nonlinear Programming problem is formulated and solved in GAMS. Significant reductions in life cycle CO_2 emissions, natural gas consumption and operating cost are achieved simultaneously in the steam and power generation system of an ethylene plant. This is an important tool to support a decision making process to reduce CO_2 emissions in a key industrial sector.

Keywords Life cycle · CO_2 · Operation · Utility plant

List of symbols

- c natural gas CO_2 content
- e CO_2 emission factor
- q fuel gas flow rate
- w imported electricity

Superscripts

- l life cycle stage
- lc life cycle

Subscripts

- h hydroelectric
- i thermoelectric power source
- ie imported electricity
- n nuclear
- ng natural gas
- rg residual gas
- t thermoelectric
- tot total
- up utility plant

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Introduction

Nowadays anthropogenic gas emissions are changing the global climate with damaging and potentially irreversible impacts on ecosystems and societies. The contribution of CO_2 emissions to global worming is relevant. The International Panel on Climate Change has strongly recommended the reduction of GHG emissions as the only way to minimize potentially irreversible impacts on ecosystems and societies. Thus, the main objective of this work is to select the optimal operating conditions of steam and power generation plants to reduce life cycle CO_2 emissions.

Life Cycle approach has been implemented by Pistikopoulos and Hugo (2005) to minimize the environmental burdens associated with the entire supply chain, the products and waste streams. Fu and Diwekar (2003) and Li et al. (2007) have proposed the minimization of cost and gas emissions with a multi objective framework for utility plants, while the former authors have worked with NO_x and SO_x emissions, the later have worked with GHG gases emissions. Li et al. (2007) also considered the life cycle emissions associated with natural gas used as fuel in the utility plant. Hashim et al. (2005) studied the Ontario energy system minimizing CO_2 emissions in a linear programming problem, although life cycle approach was not implemented. Life cycle assessment together with extended exergy analysis has been considered to elaborate an environmental performance of a steam and power plant by Corrado et al. (2006), this work present the environmental assessment of a steam and power plant that burn H_2 as fuel. Mohan and El-Halwagi (2007) develop an algebraic targeting approach of combined heat and power systems design for utilization of biomass as fuel, biomass used as fuel is cleaner than fossil fuels as it presents low green house gases emissions through net carbon recycling. The biomass utilization has higher operation cost than fossil fuels due to the present biomass processing cost. The authors also consider the CO_2 emission prices and determine the optimum cogeneration ratio.

The steam and power generation system of a petrochemical plant is the sector where fossil fuels are burned to provide utilities to the process plant. This study focuses on: (1) the estimation of life cycle CO_2 emissions of a steam and power plant and (2) the minimization of life cycle CO_2 emissions selecting optimally the operating conditions of the steam and power plant. To assess CO_2 emissions in the life cycle context a key issue is to define the life cycle boundaries extending the battery limits of the steam and power sector in order to include the main sources of CO_2 emissions such as the corresponding to the imported electricity from the national network provided by thermoelectric, hydroelectric and nuclear generation.

Typical operating conditions to be selected in utility systems are temperature and pressures of high, medium and low pressure steam headers, deareator pressure and letdowns flow rates. Binary operating variables represent discrete decision such as equipment that can be on or off as boilers and their auxiliary equipment and the selection between optional drivers for pumps that can be either electrical motors or steam turbines. As a case study the steam and power sector of an ethylene plant in operation is analyzed. Significant reductions in life cycle CO_2 emissions, natural gas consumption and operating cost are achieved simultaneously showing the importance of the methodology presented.

Modeling of the heat and power system

The utility plant provides mainly steam and power to the chemical plant. It consumes fossil fuels, a non-renewable resource burnt in the boilers and also a scarce resource as water. A schematic flow sheet of an ethylene utility plant is presented in Fig. 1.

There are four boilers B_1 to B_4 and a waste heat boiler, associated with the quenching sector of the ethane cracking furnace, that produce superheated steam at high pressure (HPS). The main equipment are: high, medium and low pressure steam headers, steam turbines, pumps, deaerator tank, vents, let-down streams, water treatment plant, vacuum condenser tank, air fans, electrical motors, heat exchangers, etc. The top product from the demethanizer column of the ethylene plant is recycled as residual gas to be mixed with the natural gas and burned in boilers and waste heat boiler.

The modeling equations of the main equipment and steam and water enthalpy and entropy property predictions are posed as equality constraints in the optimization problem formulated in GAMS (2003). The plant has alternative drivers such as electrical motors and steam turbines for some pumps. Binary variables are used for the selection of alternative drivers and some other equipment that can be on or off, like boilers and their auxiliary equipment (pumps and air fans).

Condensing and backpressure turbines are the most common types of steam turbines, with the latter having the widest application. Both can be multistage with more than one steam input or output. The output of condensing turbines commonly goes to a vacuum condenser to increase the power. Turbines take their steam from a header and release the steam to a lower pressure header. In the headers, the steam temperature and pressure is controlled by desuperheating water and by high-pressure steam letdowns. The main power demands of the process plant correspond to three compressors: cracking gas (CGC), for propylene gas (PC) and ethylene gas (EC). The condensed steam returning from the chemical process heat exchangers is collected in a tank at atmospheric pressure to be re-used and generate steam. The recycled condensate cannot be re-used without previous water treatment to prevent corrosion in boilers and turbines. There are optional drivers that can be electrical motors (M_1 to M_{11}) or steam turbines (T_1 to T_{11}) for eleven pumps in Fig. 1. A detailed mathematical model of the utility plant is presented in Eliceche et al. (2007).

Estimation of life cycle CO_2 emissions of the utility plant

The pollution comes mainly from the combustion emissions and purged water. Natural gas combustion emissions contain pollutants like CO_2, CO, NO_x, volatile organic compounds, organic hydrocarbons and trace metals. In this

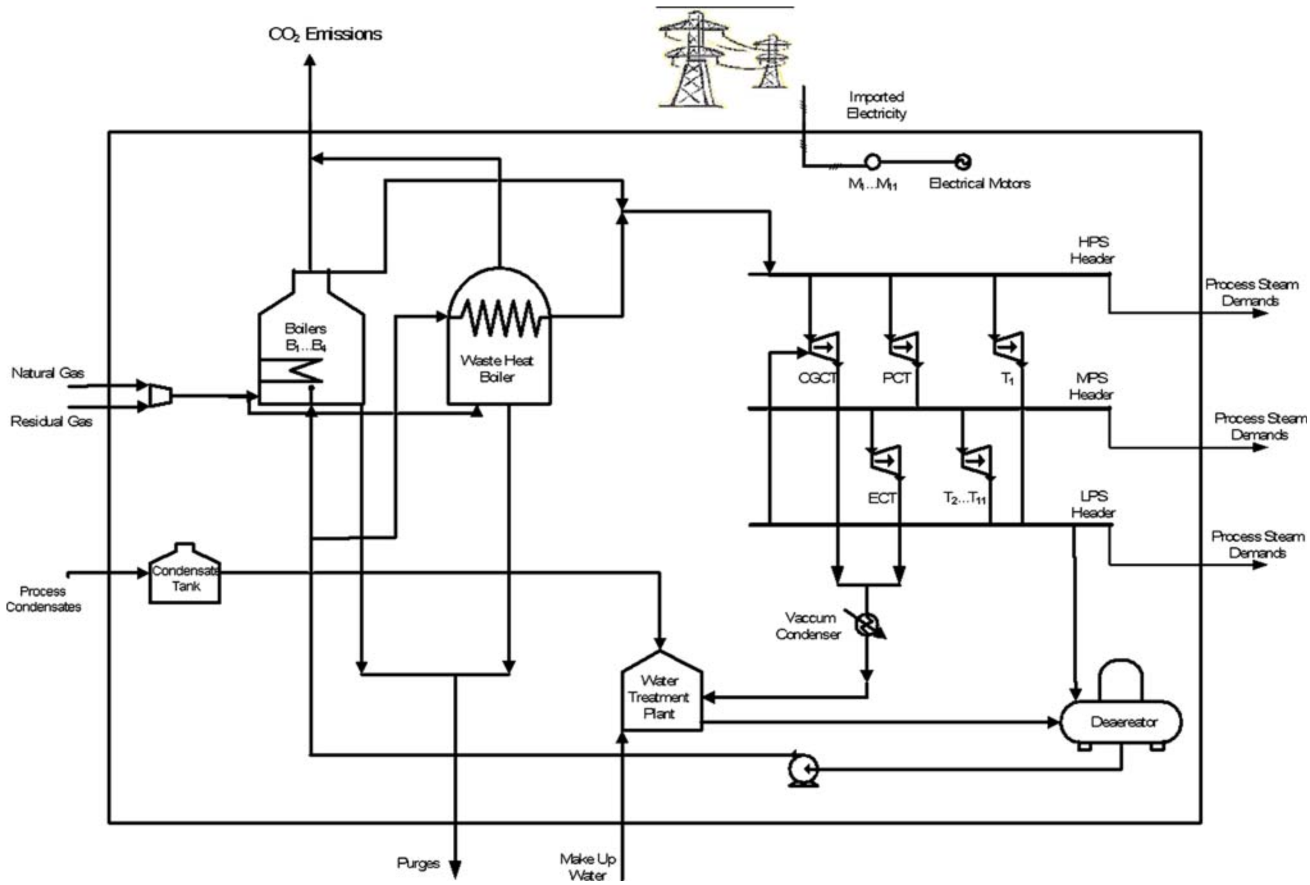


Fig. 1 Utility plant flow sheet

work, only the CO_2 emissions are considered: (1) combustion in boilers and waste heat boilers, and (2) natural gas life cycle.

Natural gas life cycle CO_2 emissions sources are mainly flaring combustion at the gas well and leakages during transportation, that are estimated from AEA report (1998) emission factors.

Both, boilers and waste heat boiler consume a mixture of natural gas and residual gas recycled from the ethylene plant. Thus the CO_2 emissions for the utility plant, including the natural gas life cycle are estimated as follows:

$$F_{UP} = q_{ng} \times \left(\sum_l e^l + c \right) + q_{rg} \times e_{rg}, \quad l = 1, \ldots, l_{ng} \tag{1}$$

where q_{ng} is the natural gas (ng) flow rate burned in the boilers; e^l are the CO_2 emission factors for each life cycle stage l; l_{ng} the total number of ng life cycle stages, including combustion in the utility plant and the natural gas fuel cycle (e.g. exploration and transport); c is the natural gas CO_2 content; q_{rg} is the residual gas flow rate coming from the top of the demethanizer column, mainly composed by H_2, that is burned in the boilers and waste heat boiler and its corresponding combustion emission factor is e_{rg}. The mass fractions of natural and residual gases as well as their CO_2 emission factors are shown in Table 1.

The mass fractions of the natural gas presented in Table 1, is a weighted average of the compositions of natural gases from different pipelines changing along the year.

Table 1 Mass fractions and CO_2 emission factors of natural and residual gases

Component	Natural gas	Residual gas
CO_2	2.00	0
H_2	0	86.05
CH_4	90.02	13.73
C_2H_6	4.70	0
C_3H_8	2.04	0
C_4H_{10}	0.91	0
C_5H_{12}	0.21	0
C_6H_{14}	0.12	0
Ethylene	0	0.22
kg CO_2/GJ	55.61	19.51

The natural gas flow rate q_{ng} burned in boilers is calculated with a rigorous simulation of the utility plant as presented in Eliceche et al. (2007). The emission factor for the generation step is taken from the USEPA AP-42 (1998) report, although plant data can also be used. The EPA report mentioned is a statistical compilation of the emissions from more than 400 boilers in the industrial sector in US. The life cycle stages considered to estimate the CO_2 emissions are shown in Fig. 2 including extraction and transport stages.

Estimation of life cycle CO_2 emissions of the imported electricity

The life cycle approach looks at the supply chain from raw material extraction, through transport, production, use and waste disposal. While process engineering is normally concerned with the operations within the battery limits (Fig. 3), life cycle thinking considers the material and energy balances in the extended life cycle boundary (Fig. 3), so that the limits between the system and the environment need to be re defined to include 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 CO_2 emissions of the imported electricity from the interconnected system, as shown in Fig. 3.

National interconnected system

The electricity generation sector in Argentina has contributions from thermoelectric, hydroelectric and nuclear plants. The share of each power source is seasonal dependent. The hydroelectric power generation depends on the rainfall regime. In thermoelectric power generation there is a variation depending on fuel availability for some power station as it is the case in those burning fuel oil or gas oil. A small quantity of electricity is produced from biomass and the quantity of electricity imported is also small. The nuclear power generation does not present a major variation during the year. There are two nuclear power plants in the country that generate around 11% of the total electricity. Yearly variations in the 1995 to 2005 period are reported in Fig. 4 and monthly variations for year 2004 are shown in Fig. 5 (Secretaría de Energía 2006). The quantity of electricity imported and generated from biomass had been added to the nuclear electricity quantity.

The estimation of life cycle CO_2 emissions due to imported electricity follows.

The overall imported electricity CO_2 emission flow rate F_{IE} is calculated as the sum of the CO_2 emission flow rates of thermoelectric F_t, hydroelectric F_h and nuclear F_n electricity imported:

$$F_{IE} = F_t + F_h + F_n \tag{2}$$

The estimation of CO_2 emission flow rates of thermoelectric F_t, hydroelectric F_h, and nuclear F_n generation plants are described in the following sections.

Thermoelectric power generation

The fuels consumed in the thermoelectric sector of the Argentinean energy system are natural gas, fuel oil, gas oil and coal using steam turbines. Gas turbines are also used with natural gas. The percentage of participation of different thermoelectric options is shown in Table 2. Natural gas represents 87% of fossil fuels burned. A small quantity of electricity from biomass (mainly wood and bagasse) is produced specially in the northern provinces of Argentina.

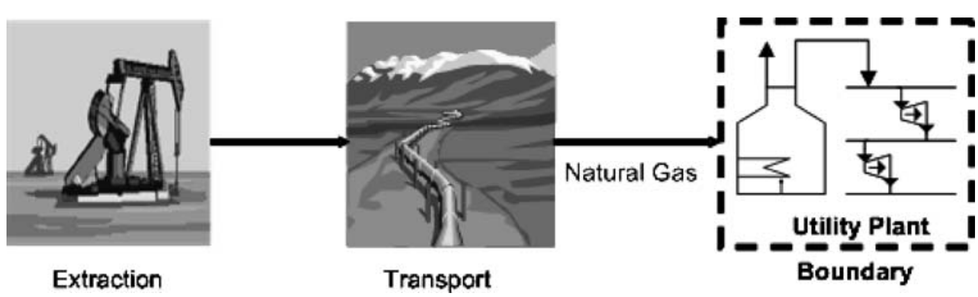
The CO_2 emissions are estimated in the: (1) generation step of each thermoelectric option and (2) fossil fuels life cycle. Exploration, extraction, transport and refining stages are considered for fuel oil and gas oil. Extraction and transport stages are considered for natural gas and coal. The emission factors published by USEPA AP-42 (1998) were used in each generation step. The emission factors for each fuel life cycle step are taken from the AEA report (1998). A graphic summary of the life cycle stages considered in thermoelectric plants is shown in Fig. 6.

Life cycle CO_2 emissions in thermoelectric plants are calculated as follows:

$$F_t = \sum_i \left(w_i \times e_i^{lc}\right), \qquad i = 1, \ldots, n_i \tag{3}$$

where i represents each thermoelectric option; n_i has a dimension of five; w_i represents the electricity imported

Fig. 2 Utility plant life cycle CO_2 emissions



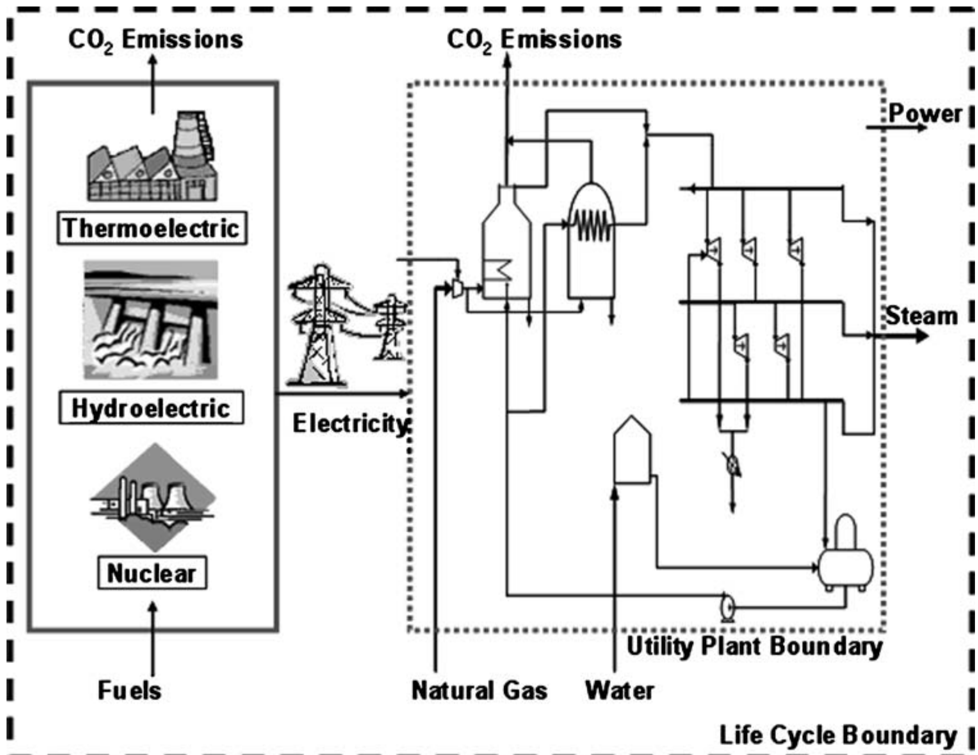


Fig. 3 Utility plant and life cycle boundaries including the imported electricity

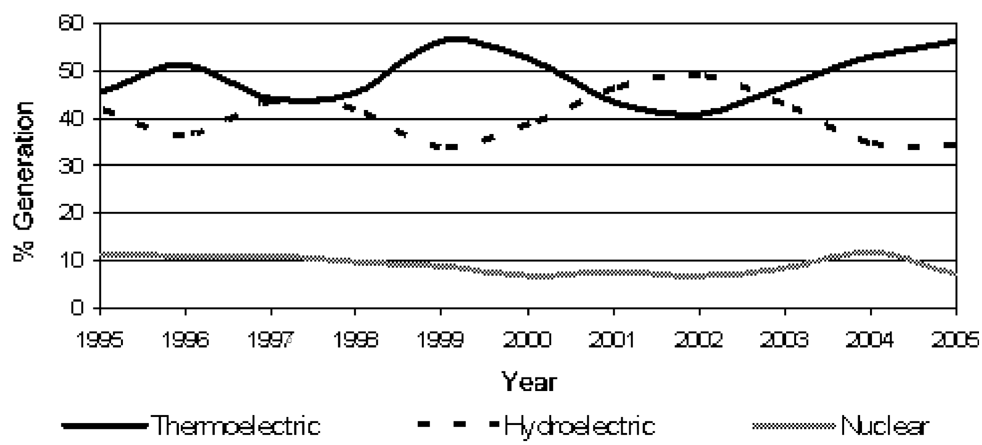


Fig. 4 Yearly variations of electricity generation in the decade 1995–2005

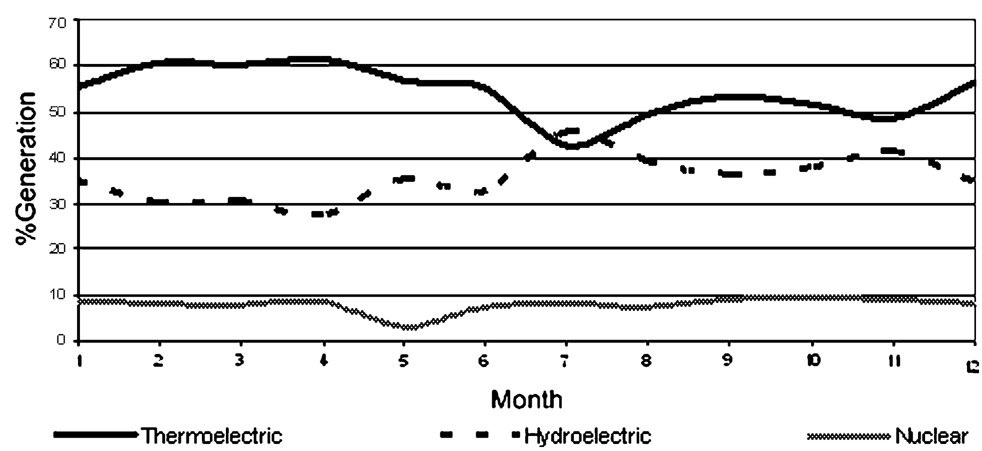


Fig. 5 Monthly variations in the electricity generation during year 2004

Table 2 Participation of different thermoelectric options for thermal generation

Fuel	Electricity generator	Participation %
Natural gas	Steam turbine	53.00
Natural gas	Gas turbine	33.61
Fuel oil	Steam turbine	7.11
Gas oil	Steam turbine	2.30
Coal	Steam turbine	3.98

from each power source i and e_i^{lc} represents the life cycle CO_2 emission factor for each type of thermoelectric power source i calculated as follows:

$$e_{\mathrm{i}}^{\mathrm{lc}} = \sum_l e_i^{\mathrm{l}}, \qquad l = 1, \ldots, l_{\mathrm{ti}} \tag{4}$$

where l_{ti} represents the total number of life cycle stages l for each thermoelectric power source i.

Hydroelectric power generation

Hydropower's air emissions are negligible because no fuels are burned. Although CO_2 emissions are estimated due to dam construction and the biomass decay (Gagnon et al. 2002). During the dam construction stage a huge amount of material is transported in trucks with internal combustion engines which emit greenhouse gases. Also, the creation of a hydroelectric reservoir contributes to greenhouse gas emissions due to the large biomass flooded during impounding that follows during the operation of dam. Gases generated by aerobic and anaerobic decomposition are mainly CO_2, CH_4, and to a lesser extent NOx, IEA (2000). Therefore, the emission factors reported by IEA (2000) have been used to estimate CO_2 emissions of transport and submerged biomass decay stages as can be seen in Fig. 7.

The CO_2 emissions associated with hydroelectric generation are calculated with the following equation:

$$F_{\mathrm{h}} = w_{\mathrm{h}} \times e_{\mathrm{h}}^{\mathrm{lc}} \tag{5}$$

where w_h represents the imported electricity from hydroelectric generation and e_h^{lc} is the corresponding overall life cycle emission factor calculated as follows.

$$e_{\mathrm{h}}^{\mathrm{lc}} = \sum_l e_{\mathrm{h}}^{\mathrm{l}}, \qquad l = 1, \ldots, l_{\mathrm{h}} \tag{6}$$

where l_h represents the total number of life cycle stages l considered for hydroelectric dams.

The CO_2 emission rate due to biomass decay is site dependent, it is affected by factors like area of reservoir, climate and amount of biomass flooded, this last factor can vary greatly, depending of the ecosystem flooded as tropical forest, peat lands, arid land, etc. (Gagnon and van de Vate 1997). Argentina has a wide variety of climate and ecosystems and almost in all of them exist a hydroelectric power plant so an average emission factor for biomass decay has been used.

Nuclear power generation

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 (1998). However fossil fuel emissions are associated with the fuel life cycle as it is the case of uranium fuel 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 due to transportation of uranium mineral in trucks. CO_2 emissions for spent fuel reprocessing and waste disposal stages have not been estimated due to lack of information available. 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.

Thus the CO_2 emissions are calculated as follow:

$$F_{\mathrm{n}} = w_{\mathrm{n}} \times e_{\mathrm{n}}^{\mathrm{lc}} \tag{7}$$

where w_n is the imported nuclear electricity. Thus the overall life cycle emission factor for nuclear electricity e_n^{lc} is estimated as follow:

$$e_{\mathrm{n}}^{\mathrm{lc}} = \sum_l e_{\mathrm{n}}^{\mathrm{l}}, \qquad l = 1, \ldots, l_{\mathrm{n}} \tag{8}$$

Fig. 6 Thermoelectric power generation life cycle

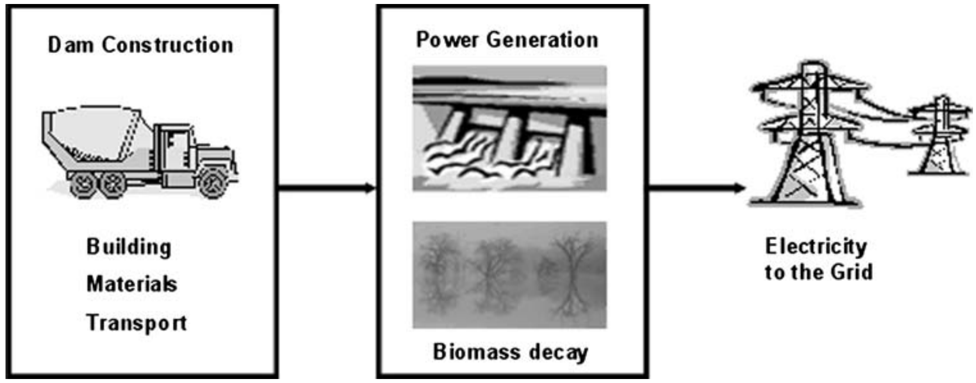


Fig. 7 Hydroelectric power generation life cycle

where l_n represents the total number of nuclear life cycle stages l considered.

Minimization of life cycle CO_2 emissions

The overall life cycle CO_2 emission flow rate F_{Tot} is calculated adding the life cycle CO_2 emission flow rates from the utility plant and the imported electricity,

$$F_{Tot} = F_{UP} + F_{IE} \tag{9}$$

The following optimization problem is formulated to select the optimal operating conditions of the steam and power plant to minimize the overall life cycle CO_2 emission flow rate F_{tot}:

$$\begin{aligned} &\underset{x,y}{\text{Min}} \quad F_{Tot}(x,y) \\ &s.t.: \quad h(x,y) = 0 \\ &\qquad g(x,y) \leq 0 \\ &\qquad x^L \leq x \leq x^U \\ &\qquad x \in R^n \\ &\qquad y \in \{0.1\}^m \end{aligned} \tag{P1}$$

where x and y are continuous and binary variables. Superscripts U and L indicates upper and lower bounds on the continuous variables x. Pressures and temperatures of high, medium and low-pressure steam headers, deaerator pressure and letdowns are the continuous operating variables, a subset of vector x. Binary variables y represent discrete decisions that allow the selection of alternative pumps drivers such as steam turbines and electrical motors and whether the boilers and their corresponding feed pumps and air fans are on or off.

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. Inequality constraints $g(x, y) \leq 0$ represent: logical constraints, minimum and maximum equipment capacities, operating and design constraints, etc. 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 system compressors. Other power demands correspond to pumps and air fans of boilers.

Selection of the operating conditions

The operating conditions of the steam and power sector of an ethylene plant in operation are evaluated to minimize life cycle CO_2 emissions. There are continuous and binary optimization variables. The continuous variables are temperature and pressure of the high, medium and low steam headers, deaerator tank pressure and letdown flow rates. Binary variables are associated to the selection of alternative pumps drivers and equipment that can be on or off. Electrical motors and steam turbines are optional drivers for lubricating pumps, condensate pumps, boiler water pumps and cooling water pumps. Boilers and their corresponding air fans and pumps can be on or off. There are 24 binary variables. A Mixed Integer Non Linear Programming problem (P1) is formulated and solved in GAMS (2003). The MINLP problem was solved with the optimization solver DICOPT; this solver uses the CONOP3 solver for NLP sub problem and CPLEX solver for MIP sub problem, respectively.

The main improvements achieved with the selection of the operating conditions solving the optimization problem P1 are presented in Table 3.

A reduction in the order of 13% in CO_2 emissions is achieved solving the MINLP problem P1. Simultaneously a reduction of 14.5% is observed in natural gas consumption, the nonrenewable fossil fuel burned in the boilers, leading to a reduction of 19% in the operating cost of the utility sector. Thus, minimizing the life cycle CO_2 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 methodology presented allows a simultaneous

Table 3 Improvements achieved minimizing life cycle CO_2 emissions

	Initial point	Optimal solution	Reduction %
Life cycle CO_2 emissions (kg/h)	32023.64	27943.45	12.74
Utility plant CO_2 emissions (kg/h)	30990.46	27586.19	10.98
Imp. elect. CO_2 emissions (kg/h)	1033.17	357.25	65.42
Operating cost ($/h)	2140.84	1728.52	19.26
Natural gas (Tn/h)	8.39	7.17	14.54
Total high pressure steam (Tn/h)	191.36	170.30	11.00
Imported electricity (K Wh)	3108.12	1074.74	65.42

Table 4 Selection of the optimal operating conditions

Optimization variable	Lower bound	Upper bound	Initial point	Solution point
HPSH pressure (bar)	48.00	52.00	50.5	52.00
MPSH pressure (bar)	18.00	26.00	23	23.84
LPSH pressure (bar)	3.00	5.00	3	4.03
HPSH temperature (°C)	400	450	420	450
MPSH temperature (°C)	310	370	320	310
LPSH temperature (°C)	150	250	210	150
Deaerator pressure (bar)	1.20	3.00	2.5	2.71

reduction of natural gas burned in boilers and also in CO_2 emissions as expected by increasing the efficiency.

Selection of temperature and pressure of steam headers

Temperature and pressure of high, medium and low pressure steam headers are calculated to minimize the life cycle CO_2 emissions and their values are reported in Table 4.

Temperature and pressure of high pressure steam header reach their upper bounds values while temperature of low pressure steam header reaches its lower bound to increase the power that can be delivered. A proper selection of temperature and pressure of steam headers is crucial to reduce natural gas consumption and life cycle CO_2 emissions.

Discrete decisions represented by binary variables

For a given configuration of alternative pump drivers the selection between steam turbines and electrical motors is carried out using binary optimization variables. Binary variables associated with a given driver have values of 1 or 0: if the value assigned solving problem P1 is 1, the optional driver has been selected and it is on; if the value assigned solving problem P1 is 0, the optional driver has not been selected and it is off. Binary variables are also used to select which boilers and their auxiliary equipment (such as pumps and air fans) are on or off.

There are four boilers in the utility plant. At the initial point of problem P1 there are three boilers on and at the solution point of problem P1 there are only two boilers on, thus the air fan and feed water pump corresponding to boiler 3 and 4 are off. Less high pressure steam is generated due to an increment of the efficiency obtained with the selection of temperature and pressure of steam headers requiring only two boilers in operation instead of three.

Nine drivers that were electrical motors at the initial point of problem P1 switch to steam turbines at the solution point, to minimize CO_2 emissions. To explain this behaviour, the ratios of CO_2 emissions with respect to power delivered between the electricity imported and the utility plant should be compared. The residual gas represents 40% of the mixture with natural gas burned in boilers and waste heat boiler. The residual gas is mainly H_2 and the natural gas is mainly methane, thus the residual gas has three times less CO_2 emissions compared to the natural gas CO_2 emissions as reported in Table 2. For this reason the CO_2 emissions to power delivered ratio is smaller in the utility plant than the average of the imported electricity. This is the case for the scenario with the following distribution: 53% of thermoelectric, 35% of hydroelectric and 12% of nuclear generation. In the thermoelectric generation: 87% of natural gas (steam and gas turbines), 9% of fuel and gas oil and 4% of carbon was considered. This work deals with the selection of the operating conditions of a utility plant, thus the scenario for the electricity generation is time dependant.

Different formulations of the optimization problem P1 could be implemented. For example problem P1 can be reformulated to achieve a specific target of CO_2 emission reduction, as it would be the case of a particular steam and power plant trying to comply with the Kyoto protocol. It is possible to use the plant specific reduction target as a constraint in the optimization problem.

Conclusions

The methodology presented is an important tool to support a decision making process to reduce Carbon Dioxide emissions, contributing to the fulfillment of the Kyoto protocol and its emission reduction targets. This methodology has been applied to the steam and power generation system, a key sector in petrochemical plants. Significant reductions have been achieved not only in Carbon Dioxide emissions (12.7%) but also in natural gas consumption (14.5%), operating cost (19%) and imported electricity (65%) as reported in Table 3. The methodology has been applied to the utility sector, although it can be extended to select the operating conditions of different industrial process plants. It is important to extend the battery limits of the process plant to consider the life cycle Carbon Dioxide emissions as it has been shown in this work, otherwise misleading results can be obtained.

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