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Carbon Price Evaluation in Power Systems for Flaring Mitigation

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ABSTRACT

This work aims to study the effect of greenhouse gases monetization to promote the reduction of flare gas. We propose to design a cogeneration system that uses natural gas as main fuel and flare gas as complementary fuel. A multi-objective nonlinear programming model is presented to determine the optimal design variables of the cogeneration system. This model maximizes the profit and minimizes the carbon dioxide equivalent simultaneously. The key factor to minimize carbon dioxide emissions is the replacement of natural gas with flare gas. Three different cases, which consider different methods to sponsor flare gas, are compared. The first case seeks to maximize the profit with trading carbon emissions. The second case also looks for maximizing the profit, however, carbon dioxide emissions are penalized by carbon taxes. In the third case, a multi-objective optimization approach based on a compromise solution that balances conflicting priorities on multiple objectives is presented. Results show that these two policy schemes work with some limitations to decrease carbon dioxide emissions. On the other hand, when the approach based on a compromise solution is used, the results show, at the same time, environmental and economic benefits.

KEYWORDS

Flare gas, Carbon tax, Trading carbon emissions, Multi-objective optimization.

INTRODUCTION

Since Kyoto protocol, several actions and international agreements have been taken in order to mitigate the climate change problem. For example, the Paris agreement looks for holding the increase in the global average temperature below 2 °C through greenhouse gases mitigation [1] and many countries have set clear strategies in this sense. For example, the European Union (EU) has put forward a goal that the share of renewable energy in energy consumption should reach 20% by 2020 [2] and to reduce total greenhouse gas emissions from EU territory with 40% by 2030, compared to 1990 levels

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[3]. However, many countries are unable to achieve their climate change strategies because implementing some of these policies in their economies is difficult [4]. Energy and environmental policies play important roles in ensuring energy supply security, coordinating energy with economic development and environmental protection, as well as addressing global climate change [5]. Carbon pricing (taxes) and carbon emissions trading are two globally practiced carbon regulatory policy schemes. The carbon pricing scheme aims to control emissions by taxing the generated carbon. Each greenhouse gas emitter is charged a tax proportional to the size of the generated emissions [6], so the prices of products and services are increased and the demand for them is reduced. The advantage of implementing a carbon tax is to encourage the use of alternative sources of energy by making them cost competitive with cheaper fuels [7]. On the other hand, in the emissions trading scheme the right to emit carbon is tradable, and the participants with high abatement costs will spend money on buying emission rights to emit more, while the participants with low abatement costs are being rewarded for their avoided emissions [8]. The biggest advantage of implementing emissions trading is to ensure that essential reductions in greenhouse gas emission targets are met at the lowest possible cost. The other main advantage of this program is to provide the private sector with the flexibility required to reduce emissions while stimulating technological innovation and economic growth. This mechanism provides financial support for greenhouse gas emission reduction projects, nevertheless, the effects in different regions and different sectors would be different under the same pattern [9]. Such program has been implemented in many US states, in the EU, and in New Zealand and Australia [7]. Mentioned price incentives and economic penalties (monetization) are common approaches to control water usage and total direct greenhouse gas emissions (externalities) of industrial processes [10]. Some countries have already introduced a carbon tax or carbon emissions trading system, nevertheless, most countries are still hesitant to take actions or currently remain in a cautious wait-and-see attitude [11]. There are many reasons why some countries are cautious in including these policies. Specially, because carbon markets cannot be sufficiently sustained without government assistance and intervention [12], furthermore, pushing relatively costly alternative for energy technologies into the market increases the overall social cost of climate protection and reduces the efficiency of policy intervention. In this way, alternative energy-subsidies could also reduce public acceptance of renewable energies and thus may reduce the political leeway for climate protection in general [13].

Transport, electricity and heat production are some of the main contributors to total greenhouse gas emission in most countries, particularly in the industrial sector, and there are several researches in this area. However, one of the key factors to achieve the Paris agreement is gas flaring reduction. Flares are open flames used for disposing waste fuel gases during normal and abnormal operations. They are used as safety devices and they achieve 98% of destruction efficiency [14], nevertheless, this practice is responsible of contributing 400 million tonnes per year of carbon dioxide equivalent (CO_2eq) [15], which contribute to the climate change and affect all the fossil fuels producing countries. The World Bank Group has a leadership role in the initiative for gas flaring reduction through the global gas flaring reduction partnership, and some legislations have been proposed to promote the minimization of emissions.

In many cases, the success of flare gas reduction technologies is supported by monetization of emission. Moreover, because flared gas represents a serious problem, several alternatives to eliminate or reduce gas flaring have been reported. This way, Stanley [16] examined the prospect of Gas-to-Liquid (GTL) technology in Nigeria to convert natural gas, wasted through the continuous flaring, into more suitable fuels for transportation like diesel, naphtha and kerosene. The first step in GTL technology is to convert natural gas into syngas, which is produced using partial oxidation or steam reformation. Then, the syngas is converted to long-chain hydrocarbon molecules via

Fischer-Tropsch process, and finally long-chain hydrocarbons are fed into a cracking unit and fractioned into liquid fuels. The products of GTL technology are sulfur free and flexible to replace other similar products, therefore, countries with huge natural gas resources can find in GTL an alternative to flare gas [16]. Comodi *et al*. [17] proposed flare gas recovery as a method to improve energy efficiency in oil refineries and decrease greenhouse gas emissions. Particularly, they selected a liquid ring compressor technology, which is a rotary volumetric machine that uses a secondary fluid to compress the flare gas. As expected, the presence of inert gas and hydrogen sulphide, and a strongly variable flow rate and composition were the main problems, however, they reported environmental and economic advantages using this method [17]. Also, Hajizadeh *et al*. [18] presented an evaluation of three methods of flare gas recovery in a gas refinery in Iran including liquefaction, liquefied petroleum gas production and gas compression for returning flare gas to refinery inlet stream, and their results showed that using flare gas recovery methods more that 80% of flare gases can be recovered [18]. Another alternative is to use flare gas to produce electricity. It has several advantages like reduction of gas consumption, simple preparation of the required equipment and its affordable costs. To produce electricity, usually a cogeneration system is implemented, which has higher efficiencies than conventional power generation systems. Cogeneration can provide a wide variety of utilities, including heating, cooling and electricity. Furthermore, cogeneration can be fed with different fuels, and the available technology can be adapted to manage flare [19]. Heidari *et al*. [19] presented a study where two methods were introduced to use flare gas as a fuel for electricity generation considering variable flow rate and low LHV of flare gas, which use natural gas as a complementary fuel for flare gas. Furthermore, it is possible to find examples of power generation using flare streams and carbon regulatory policy schemes in literature. Kazi *et al*. [20] proposed an optimization model for sizing a cogeneration system for flaring mitigation in an ethylene plant. The idea was to use flaring streams in cogeneration units to produce heat and power, which can be used to satisfy the process needs or exported to generate extra revenues. Also, the results showed economic and environmental benefits [20]. Kazi *et al*. [21] extended the mentioned optimization framework to study the benefits of integrating a flare mitigation tool with a wastewater treatment facility to mitigate flaring and increase the process efficiency [21].

The utilization of each technology depends on the characteristics of the flare streams, however, it has been demonstrated that electricity generation is economically superior [22]. Rahimpour and Jokar [22] compared GTL technology, electricity generation and gas recovery in Farashban gas refinery to recover flare gas instead of conventional gas burning in flare stacks. The electricity production gives the highest rate of return and annual profit, moreover, the lowest payback period. Zolfaghari *et al*. [23] found electricity production as one of the most economical ways to recover flare gas when they compared this method with GTL and gas to ethylene processes.

This paper presents a multi-objective formulation based on a compromise solution that balances conflicting priorities of multiple stakeholders on multiple objectives (environmental and economic objectives). This formulation is compared with the typical mono-objective problem where an economic function includes the environmental cost in terms of carbon tax savings or trading carbon emission. We argue that it is more effective to encourage the use of environmentally friendly alternatives using a compromise solution than monetization. To the best of our knowledge, a study that compares these two alternatives in flaring mitigation systems has not been reported.

PROBLEM STATEMENT

We consider a set of flare streams from distinct plants in an oil refinery, whose mixture has the potential to be used as complementary fuel in a cogeneration system as shown in Figure 1. If this operation results in economic and/or environmental benefits, the energy of flare streams can be exploited. On the other hand, if feeding cogeneration system with the mentioned flare gas brings economic losses and/or environmental problems, flare streams must be burned into the atmosphere, as traditionally done, using a flare system.

The cogeneration system is dimensioned according to a range of minimum and maximum electricity production to satisfy plant necessities with the options to use natural gas, flare streams or a mix of both as fuel. It is assumed that the characteristics of the blend remain constant during the operation, therefore, the use of waste gas fuel does not affect the performance of the system. Also, the flare gas mass flow stays constant all the time. Then, the problem consists in determining the optimal size of the system to produce power utilizing flares, while maximizing profit and minimizing CO_2eq. The main contribution of this work is to study the impact of giving an economic value or penalization to the emission with the goal to promote the use of technology to reduce gas flaring. Therefore, two different cases are solved to analyze the result of using the externalization of carbon dioxide emissions as a way to decrease flaring versus a proposed multiobjective formulation based on a compromise solution that gives the same importance to the reduction of emissions and to the economic feasibility.

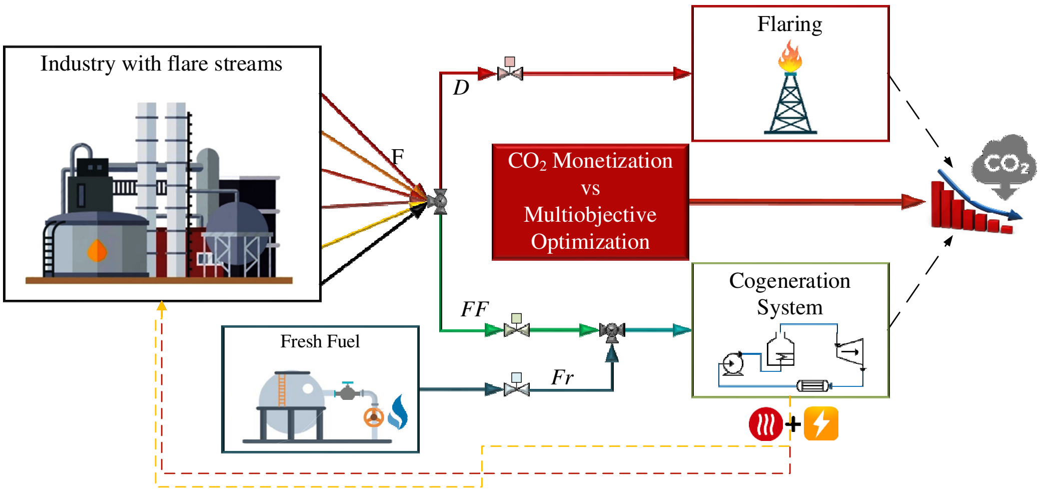

Figure 1. Superstructure of the proposed system

Physical model

The mathematical formulation is derived from a previously published scenario-based optimization approach [24]. The mentioned work seeks to design a cogeneration system that can be fed with flares and natural gas simultaneously, moreover, it considers the uncertainty of the flare stream flow and natural gas (fresh fuel) prices employing one hundred random scenarios (s) for these parameters. The flare stream ($F_{i,t,s}$) is a mixture of different waste fuel streams (i) with distinct composition and mass flow that change over time (t). In this project, the model includes similar mass and energy balances, cost functions and emission calculations to represent the superstructure shown in Figure 1. However, in order to study the effect of trading carbon emission and carbon taxes in gas flaring reduction, the uncertain scenarios are not taken into consideration and it is assumed that the mass flow for flare streams (F) and their physical properties remain constant. In this section, the modified mathematical model is presented in a deterministic way.

The first expression involves the total mass balance of the waste fuel stream. The stream (F) can be burned in the open atmosphere using the flare system (D), sent to feed the cogeneration system (FF) as supplementary fuel, or divided to burn a fraction in the flare stack and take advantage of the rest:

$$F = D + FF \tag{1}$$

Also, a set of relationships is needed that represents the energy balance in the cogeneration system. The heat generated by the boiler (Q^{boil}) is equal to the sum of the energy obtained from fresh fuels ($Fr\,H^{\mathrm{Fr}}$) and the flare gas sent to the boiler ($FF\,H^{\mathrm{FF}}$) times the equipment efficiency (η^{boil}):

$$Q^{\mathrm{boil}} = \eta^{\mathrm{boil}} \left(Fr\,H^{\mathrm{Fr}} + FF\,H^{\mathrm{FF}} \right) \tag{2}$$

The energy balance in the boiler $\left(Q^{\mathrm{boil}}\right)$, turbine $\left(P^{\mathrm{turb}}\right)$, condenser $\left(Q^{\mathrm{cond}}\right)$, and pump $\left(P^{\mathrm{pump}}\right)$ can be used to determine the water mass flowrate (m) in the steam Rankine cycle, which must consider the outlet and inlet enthalpies as follows:

$$Q^{\mathrm{boil}} = m(h_1 - h_4) \tag{3}$$

$$P^{\mathrm{turb}} = m\,(h_1 - h_2) \tag{4}$$

$$Q^{\mathrm{cond}} = m\,(h_2 - h_3) \tag{5}$$

$$P^{\mathrm{pump}} = m(h_4 - h_3) \tag{6}$$

The profit for the energy sales $\left(\mathrm{Sales}^{\mathrm{elect}}\right)$ is calculated as a function of the power produced in the cogeneration system $\left(P^{\mathrm{turb}}\right)$ and the market price $\left(\mathrm{price}^{\mathrm{elect}}\right)$:

$$\mathrm{Sales}^{\mathrm{elect}} = P^{\mathrm{turb}}\,\mathrm{price}^{\mathrm{elect}} \tag{7}$$

The steam used in Rankine cycle (m) is limited by a maximum allowed flowrate $\left(m^{\max}\right)$, and it can be calculated as a function of the turbine capacity $\left(P^{\mathrm{turb}}\right)$:

$$m \le m^{\max} \tag{8}$$

$$m = C1_{\mathrm{m}}\, P^{\mathrm{turb}} + C2_{\mathrm{m}} \tag{9}$$

Then, there are considered the operating cost for the condenser $\left(OC^{\mathrm{cond}}\right)$, pump $\left(OC^{\mathrm{pump}}\right)$ and fresh fuel $\left(OC^{\mathrm{rep}}\right)$. The operating costs for the needed units are determined as functions of equipment capacity $\left(Q^{\mathrm{cond}} \text{ and } P^{\mathrm{pump}}\right)$ and fresh fuel flow $\left(Fr\right)$.

$$OC^{\mathrm{cond}} = Q^{\mathrm{cond}}\,\mathrm{price}^{\mathrm{cw}} \tag{10}$$

$$OC^{\mathrm{pump}} = P^{\mathrm{pump}}\,\mathrm{price}^{\mathrm{power}} \tag{11}$$

$$OC^{\text{rep}} = Fr\, H^{\text{Fr}}\, \text{price}^{\text{rep}} \quad (12)$$

The cost of combusting flare streams as supplementary fuel is calculated using the method of Ulrich and Vasudevan [25]. First, the utility cost coefficients (*A* and *B*) are calculated using eq. (13) and eq. (14). *LHV* and waste gas flows (q) [Nm^3/s] are used to find the coefficients:

$$A = \left(2.5\times10^{-5}\, LHV^{0.77}\right) q^{-0.23} \quad (13)$$

$$B = -6\times10^{-4}\, LHV \quad (14)$$

Afterward, the utility cost coefficients (*A* and *B*) are used to calculate the cost per Nm^3 of waste fuel gas (CSU) using the next equation:

$$CSU = A\times CEPCI + B\times CSF \quad (15)$$

Finally, eq. (16) calculates the cost of using flare streams as supplementary fuel to feed the cogeneration system (OC^{flow}). Also, this equation uses a conversion factor to compute this cost in USD per month:

$$OC^{\text{flow}} = 2.592\times10^{6}\, q\, CSU \quad (16)$$

The equations to calculate equipment capital cost were taken from literature [26]. This way, the boiler (CC^{boil}), turbine (CC^{turb}), condenser (CC^{cond}), and pump (CC^{pump}) capital costs involve a fixed part (CF) as well as a part that depends on the unit size (CV) elevated at the exponent (c) to account for the economies of scale:

$$CC^{\text{boil}} = CF^{\text{boil}} + CV^{\text{boil}} (Q^{\text{boil}})^{c^{\text{boil}}} \quad (17)$$

$$CC^{\text{turb}} = CF^{\text{turb}} + CV^{\text{turb}} (P^{\text{turb}})^{c^{\text{turb}}} \quad (18)$$

$$CC^{\text{cond}} = CF^{\text{cond}} + CV^{\text{cond}} (Q^{\text{cond}})^{c^{\text{cond}}} \quad (19)$$

$$CC^{\text{pump}} = C1^{\text{pump}} + C2^{\text{pump}}\, (P^{\text{pump}})^{c^{\text{pump}}} \quad (20)$$

It should be noted that the power generated by the Rankine cycle (P^{turb}) must be lower than the maximum demand ($EMAX$) and greater than the minimum required ($EREQ$), which is modelled as follows:

$$P^{\text{turb}} \leq EMAX \quad (21)$$

$$P^{\text{turb}} \geq EREQ \quad (22)$$

Greenhouse gas emissions (CO_2eq) produced by the cogeneration system ($GHGCS$) take into account the emissions produced by combustion of fresh fuel (Fr) and combustion of flares (FF):

$$GHGCS = \sum_{c}\left(\frac{FF\ X_{c}\ Y_{c}}{PM_{c}}\right)\left(PM_{CO_2}\right) + \sum_{cFr}\left(\frac{Fr\ X_{cFr}\ Y_{cFr}}{PM_{cFr}}\right)\left(PM_{CO_2}\right) \tag{23}$$

Furthermore, the emissions (CO_2eq) produced by flare streams when flare gases are not exploited ($GHGFS$) are calculated in a similar way:

$$GHGFS = \sum_{c}\left(\frac{D\ X_{c}\ Y_{c}}{PM_{c}}\right)\left(PM_{CO_2}\right) \tag{24}$$

Therefore, total emissions (CO_2eq) generated by the whole system ($TGHG$) are the sum of the emissions for flares ($GHGFS$) and emissions from the cogeneration system ($GHGCS$):

$$TGHG = GHGCS + GHGFS \tag{25}$$

The objective function was formulated for three different cases to compare the effect of monetization in greenhouse gas reduction versus a multiobjective solution that aims to simultaneously minimize the emissions and maximize the profit.

The objective function changes in each case as follows.

<u>Case 1</u>. The first case looks to maximize the profit as presented in eq. (26a). Flaring mitigation is promoted through carbon emissions trading, so it is expected that the carbon dioxide emissions can be reduced due to an economical compensation for each tonn of CO_2eq avoided. Table 1 shows the values that take the parameter *CTrad* in each scenario of Case 1:

$$\text{Profit} = \text{Sales}^{\text{elect}} - OC - k_{F}\left(CC\right) + CTrad(GHG^{UB} - TGHG) \tag{26a}$$

<u>Case 2</u>. The second case seeks to maximize the profit as previously presented, however, the reduction of emissions is promoted through an economic penalization per tonn of CO_2emitted. Table 2 presents the cost per tonn that the parameter *CTax* has in each scenario of Case 2:

$$\text{Profit} = \text{Sales}^{\text{elect}} - OC - k_{F}\left(CC\right) - CTax(TGHG) \tag{26b}$$

<u>Case 3</u>. The last case looks to simultaneously maximize the profit and minimize the greenhouse gas emissions. Neither carbon pricing nor carbon emission trading intervene in this case. Here, different weights are assigned to each objective (see Table 3) to analyze its behavior as presented in eq. (26c):

$$FO = w_{1}\left(\frac{\text{Profit}^{UB} - \text{Profit}}{\text{Profit}^{UB} - \text{Profit}^{LB}}\right) + w_{2}\left(\frac{TGHG - GHG^{LB}}{GHG^{UB} - GHG^{LB}}\right) \tag{26c}$$

Table 1. Prices per tonn of CO_2eq in carbon emission trading (Case 1)

Scenario	1	2	3	4	5	6
Price CO_2eq [USD/tonn]	3	10	15	30	80	120

Table 2. Cost per tonn of CO_2eq in carbon pricing (Case 2)

Scenario	1	2	3	4	5	6
Cost CO_2eq [USD/tonn]	10	15	25	32	41	52

Table 3. Different values to weight priorities in multi-objective equation (Case 3)

Scenario	1	2	3	4	5	6	7
w_1	1	0.8	0.6	0.5	0.4	0.2	0
w_2	0	0.2	0.4	0.5	0.6	0.8	1

The proposed mathematical model is nonlinear, and it is solved in JuMP [27] (Julia for Mathematical Optimization) using Ipopt [28].

CASE STUDY

The case study considers an oil refinery (as shown in Figure 1) with a continuous flow of a flare gas mixture (2.22 kg/s). This potential energy source is burned in a flare stack system. However, it is proposed as a possibility to use the entire or a fraction of the stream to feed a new cogeneration system. The available quantity of flare gas is not enough to satisfy the energy requirements of the industrial complex by themselves, so there is a main stream of fresh fuel (natural gas), which can supply partially or totally the needed energy. The minimum required power, and the maximum allowed power to produce with cogeneration system are 32 MW and 64 MW, respectively. The use of flare gas is important because it helps to decrease the necessity of external energy and the refinery takes advantage of waste energy. Therefore, it is intended to design a cogeneration system that can handle with a mixture of natural gas and flare gas.

Table 4 and Table 5 show the properties, flows and compositions of the fresh fuel and flare gas. In order to solve the three proposed cases, using different methods to decrease carbon dioxide emission, these data are adapted from literature [19].

As mentioned before, we have three cases. The first case uses the prices shown in Table 1 to study the effect of carbon emission trading in emission reduction. The second one analyzes the behavior of the system when carbon taxes push the model to invest in the proposed energy recovery technology. The last case weights both objectives (Table 3), economic and environmental, to investigate the effect of prioritizing one of them in flare mitigation.

Table 4. Flare stream and fresh fuel properties

Flare stream properties			Fresh fuel properties		
Flow [kg/s]	Molecular mass	Heating value [GJ/tonn]	Flow [kg/s]	Molecular mass	Heating value [GJ/tonn]
2.22	39.92	33.44	Unlimited	17.29	45.9

Table 5. Flare gas mixture composition

Gas	Composition [%]	Gas	Composition [%]
Nitrogen	0.60	n-pentane	2.60
Water	3.10	Pentane	2.70
Carbon monoxide	0.00	Benzene	3.20
Carbon dioxide	28.00	Toluene	2.80
Methane	36.00	Xylene	2.20
Ethane	7.20	Naphthalene	2.50
Propane	4.90	Isobutene	1.40
n-butane	2.80		

Next section presents the results for each mentioned case. The behavior of the system is presented in graphics that show the impact of monetization and the results to have a compromise solution.

RESULTS AND DISCUSSION

Figure 2 shows reference values without considering monetization or the multi-objective function. The first point is obtained when the profit is maximized [max(Profit)]. In this solution, the cogeneration system takes the maximum allowed capacity (64 MW), but flare gas is not used as complementary fuel because it implies a cost. Then, this point has the maximum value of CO_2eq and the maximum profit. The opposite point is calculated when the emissions (CO_2eq) are minimized [min(*TGHG*)]. If the CO_2eq is minimized, the cogeneration system takes the minimum required capacity (32 MW), and all flare gas is used as complementary fuel no matter what the cost is, so this point represents the solution with the minimum emissions and the worst profit. Starting from these solutions, one may define the utopia point [the utopia point is the ideal unreachable point where all the objectives are independently minimized (UP)] and nadir point [the nadir point is the point of worst objective values (NP)]. Both points are infeasible solutions, nevertheless, they are reference points because the idea is to be far from the nadir point and to be as close as possible to the utopia point.

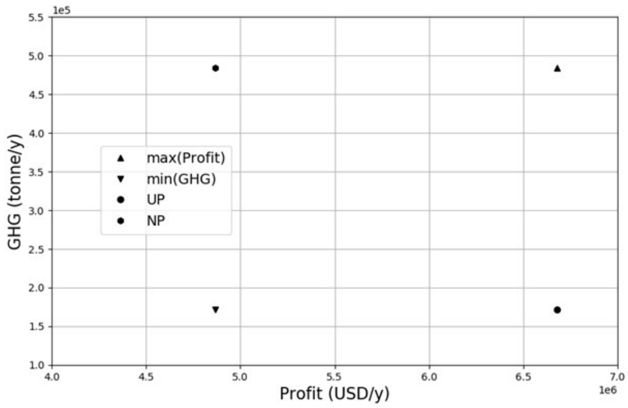

Figure 2. Reference solutions

Figure 3 presents the solution for Case 1, where eq. (26a) is the objective function. The problem is solved for different prices of carbon dioxide emissions as shown in Table 1. The blue triangles in Figure 3 represent the solution when carbon emission trading is used to promote flare reduction. It can be noted that when emissions have a price between 3 and 15 USD per tonn, it is not convenient to invest in flare mitigation, so emissions remain in the maximum value. Moreover, the capacity of the cogeneration system reaches the maximum allowed value in these cases. When the price rises to 30 USD per tonn, the profit increases and emissions decrease 35%. However, this reduction is associated with the cogeneration system, which changes its capacity from 64 MW to 32 MW, and unfortunately flare gas is not burned into the cogeneration system. To decrease emissions to the minimum value (i.e., using the minimum capacity for cogeneration and using all flare gas as complementary fuel), it is necessary to have a price per tonn higher than USD 80, which is a goal hard to reach.

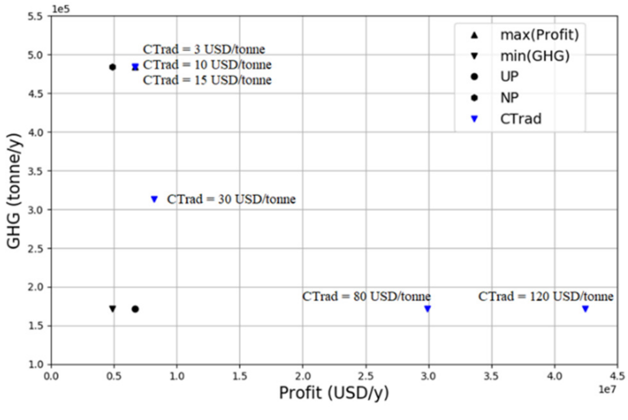

Figure 3. Results for carbon emission trading (Case 1)

Figure 4 shows the obtained results when eq. (26b) is maximized using the carbon tax costs of Table 2. As it can be seen in Figure 4, carbon tax in scenarios 1 to 3 does not have influence in carbon dioxide mitigation, moreover, when carbon tax increases in scenarios 4 to 6 there is no profit and the minimum emissions value cannot be achieved even with the highest carbon tax. In this case, the flare gas is not used in any scenario as complementary fuel, and the capacity of cogeneration system is 64 MW for scenarios 1 and 2, and 32 MW for scenarios 3 to 6.

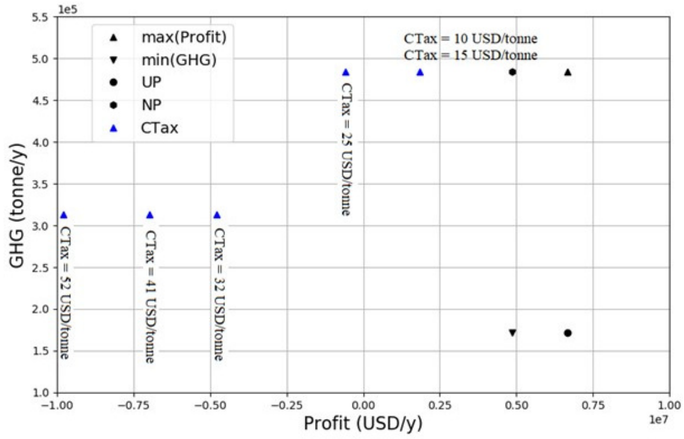

Figure 4. Results for carbon pricing (Case 2)

Figure 5 displays the results to maximize the Compromise Solution (CS) presented in eq. (26c). The red and blue points are the reference points presented in Figure 1, and the black points represent the compromise solution. The black points that overlap the blue points are the extreme values of the compromise solution (w_1 and w_2 take the values of scenario 1 and 7 in Table 3). The solutions for scenarios 2 to 6 are placed in the same point (black point). The power capacity of the cogeneration system in case 3 is superior to cases 1 and 2. The power generated in the compromise solution is 48.29 MW, and it is observed that the compromise solution has the maximum profit and it presents an important reduction of carbon dioxide emission. Carbon dioxide emissions in the compromise solution are only 15% greater than the minimum value. It is important to note that in case 3 all the flare gas is used as complementary fuel, even when carbon pricing or carbon emissions trading are not used. Therefore, this multi-objective strategy is a better way to encourage flaring mitigation than monetization. When it is used carbon emissions trading, a very high price per tonn of CO_2eq is required, and when it is utilized the carbon tax strategy the profit results more severely affected than emissions.

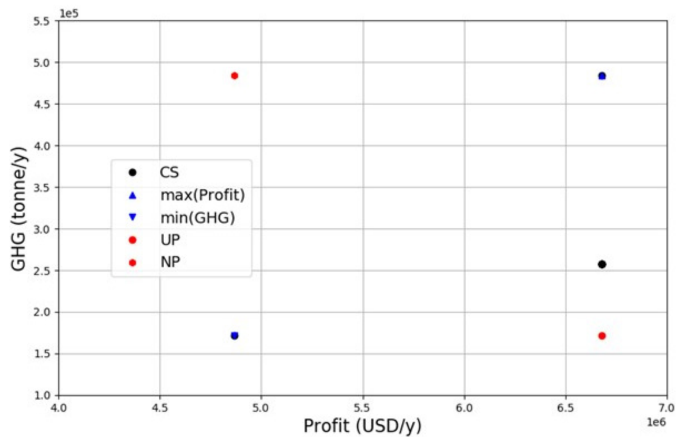

Figure 5. Results for multiobjective formulation (Case 3)

CONCLUSION

The presented formulation helps to analyze the performance of monetization as stimulus to invest in flare reduction mechanisms. The proposed model can be used to solve different case studies using the appropriated data. A case study was presented to show the economic and environmental effect of monetization in flaring reduction, and it was demonstrated that carbon pricing or carbon emissions trading are not the best methods to promote alternative technologies in flaring management. To use a compromise solution, as presented in this work, offers a solution close to the utopia point, furthermore, it was shown that when a new technology for flare mitigation is introduced to an existing process, it is not necessary to reduce the profit in order to have a substantial reduction of greenhouse gas emissions. Moreover, the use of multiobjective optimization methods in the design or selection of technology result in environmental and economic benefits and it allows to keep away the uncertainty related to monetization.

NOMENCLATURE

A	utility cost coefficient, which reflects inflation-dependent cost elements	[-]
B	utility cost coefficient, which reflects energy-dependent cost elements	[-]
$C1^{pump}$	constants for the equation of the pump capital cost	[-]
$C1_m$	constants for the equation of the steam used in Rankine cycle	[-]
$C2^{pump}$	constants for the equation of the pump capital cost	[-]
$C2_m$	constants for the equation of the steam used in Rankine cycle	[-]
c^{boil}	constant for the equation of boiler capital cost	[-]
c^{cond}	constant for the equation of the condenser capital cost	[-]
c^{pump}	constant for the equation of the pump capital cost	[-]
c^{turb}	constant for the equation of the turbine capital cost	[-]
$CBon$	price of CO_2 in carbon emissions trading	[USD/tonn]
CC^{boil}	boiler capital cost	[USD/y]
CC^{cond}	condenser capital cost	[USD/y]
CC^{pump}	pump capital cost	[USD/y]
CC^{turb}	turbine capital cost	[USD/y]
$CEPCI$	chemical engineering plant cost index	[-]
CF^{boil}	boiler fixed cost	[-]
CF^{cond}	condenser fixed cost	[-]
CF^{cond}	condenser variable cost	[-]
CF^{turb}	turbine fixed cost	[-]
CSF	fresh fuel cost	[USD/Nm^3]
CSU	utility price	[USDNm^3]
$CTax$	price of CO_2 in carbon tax system	[USD/tonn]
CV^{boil}	boiler variable cost	[-]
CV^{turb}	turbine variable cost	[-]
D	flare flowrate sent to the flaring system	[tonn/month]
$EMAX$	energy to satisfy the requirements inside and outside the plants	[GJ/month]
$EREQ$	energy required to satisfy the plant demands	[GJ/month]
F	flare streams from different plants	[tonn/month]
FF	flare flowrate sent to the cogeneration system	[tonn/month]
FO	objective function in the multi-objective optimization	

Fr	fresh fuel fed to the cogeneration system	[tonn/month]
GHGCS	GHG generated by the cogeneration system in each scenario	[tonn/y]
GHGFS	GHG generated by the flaring system in each scenario	[tonn/y]
GHG^{LB}	minimum quantity of carbon dioxide that the system can generate	[tonn/y]
GHG^{UB}	maximum quantity of carbon dioxide that the system can generate	[tonn/y]
h_1	water enthalpy at the boiler outlet	[GJ/tonn]
h_2	water enthalpy at the turbine outlet	[GJ/tonn]
h_3	water enthalpy at the condenser outlet	[GJ/tonn]
h_4	water enthalpy at the pump outlet	[GJ/tonn]
H^{FF}	heat content of flare streams of the plants	[GJ/tonn]
H^{Fr}	heat content of fresh fuel	[GJ/tonn]
k_F	annualization factor	[-]
LHV	low heating value	[GJ/Nm^3]
m	water mass flow in cogeneration system	[kg/s]
m^{max}	maximum water flow in the cogeneration system	[kg/s]
OC^{cond}	condenser operating cost	[USD/y]
OC^{flow}	operating cost for flare streams as supplementary fuel	[USD/y]
OC^{pump}	pump operating cost	[USD/y]
OC^{rep}	fresh fuel cost	[USD/y]
P^{pump}	energy consumed by the pumps	[GJ/y]
P^{turb}	power generated by the turbine	[GJ/y]
PM_c	molecular weight for each component	[kg/kmol]
PM_{cFr}	molecular weight for fresh fuel	[kg/kmol]
PM_{CO_2}	molecular weight for carbon dioxide	[kg/kmol]
Profit	profit	[USD/y]
price^{cw}	cooling water price	[USD/GJ]
price^{elect}	electricity price	[USD/GJ]
price^{power}	power price	[USD/GJ]
price^{rep}	fresh fuel price	[USD/GJ]
Profit^{LB}	profit lower bound	[USD/y]
Profit^{UB}	profit upper bound	[USD/y]
q	total waste gases used as supplementary fuel	[Nm^3/s]
Q^{boil}	energy generated by the boiler	[GJ/y]
Q^{cond}	energy removed by the condenser	[GJ/y]
Sales^{elect}	profit by generated electricity	[USD/y]
TGHG	total GHG generated by the entire system in each scenario	[tonn/month]
w_1	parameter that reflects the economic priority	[-]
w_2	parameter that reflects the environmental priority	[-]
X_c	stoichiometric constant for each component	$\left[\text{kg}_{CO_2}/\text{kg}_C\right]$
X_{cFr}	stoichiometric constant for fresh fuel	$\left[\text{kg}_{CO_2}/\text{kg}_C\right]$
Y_c	mole fraction of each component	[-]
Y_{cFr}	mole fraction of each component for fresh fuel	[-]

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