COMPARISON OF THE COSTS AND GHG EMISSIONS OF DIFFERENT TREATMENT METHODS FOR CTMP PULP AND PAPER WASTEWATER

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Abstract: The atmospheric concentration of carbon dioxide which constitutes the major greenhouse gas (GHG) has increased significantly after the industrial revolution. Many attempts have been made aiming at the reduction of CO_2 in the atmosphere. In the present study, a hybrid treatment process is developed for CO_2 removal from wastewaters generated by industrial operations. In the developed process, a CO_2-saturated wastewater enters an anaerobic reactor where CO_2 is bioconverted to methane, followed by an aerobic reactor for additional treatment of the wastewater. This study evaluates the economic feasibility of the developed hybrid treatment process to treat CTMP wastewater from the pulp and paper industry, making a comparison of this process with the aerobic and conventional hybrid (anaerobic/aerobic) treatment systems. The GoldSET^{TM} software is applied to compare various treatment methods based on their corresponding economical, environmental and social aspects. The anaerobic and aerobic treatment systems in the present case study use IC (internal circulating) and activated sludge processes, respectively. The results show the advantages of the developed hybrid treatment process compared to the conventional hybrid and aerobic treatment methods.

1 INTRODUCTION

Global warming became a serious issue after the industrial revolution in the eighteenth century. Every year a large amount of GHGs are emitted to the atmosphere. The world bank group (TWBG) reported 728 $MtCO_2e$ emission in 2012 for Canada (TWBG 2014). According to the National Ocean and Atmospheric Administration (NOAA), the concentration of carbon dioxide in the atmosphere increased from 316 ppm in 1960 to 399.65 ppm in January 2015 (NOAA 2015). Therefore, long term solutions for carbon dioxide reduction must be investigated that are environmentally safe, economically efficient, and socially acceptable. There are certain policies that help countries to manage and reduce their GHG emissions such as carbon offset which is a credit given to one party for reduction of CO_2 or other GHGs. It is estimated that the carbon credit market transacted over CAD$139 billion in 2008 which was twice its value in 2007 (Carlson et al. 2009). Biological treatment of wastewater has the potential to attain revenue as carbon credits for the wastewater treatment plant. Methane generated in anaerobic treatment can be collected and used as a renewable source of energy. The combustion of methane instead of fossil fuels offsets the CO_2 emission from fossil fuels. On the other hand, the CO_2 generated from the combustion of recovered methane is not a GHG and is considered as a neutral CO_2.

With respect to the importance of GHG emission reduction, a sustainable hybrid treatment system is developed to reduce carbon dioxide emissions (Abedi et. al 2012). In this method, industrial emissions containing CO_2 are injected into a wastewater stream while entering the anaerobic reactor. Accordingly, by anaerobic treatment of wastewater, CO_2 is biologically converted to methane as a biogas with a high efficiency through a highly sustainable process. This conversion is based on the last step of anaerobic digestion process in which CO_2 is used as a substrate by bacteria to produce methane. Anaerobic treatment is followed by aerobic treatment for additional COD removal. A spray scrubber is applied to saturate the wastewater with CO_2 by increasing the contact between liquid wastewater and the flue gas without using any alkaline solution. By applying the scrubber, the capacity of wastewater to dissolve CO_2 increases from 1.3 g/l without using a scrubber (Web 1) to 10.3 g/L at the temperature of 35 ^oC, liquid flow rate of 200 ml/min and gas flow rate of 2.5 L/min (Kazemi 2013).

The results of continuous operation of the developed process by Abedi (2012) showed that almost 100% of the excess $CO_{2\ (aq)}$ dissolved in the wastewater by applying a scrubber was converted to methane.

The present paper reports on the comparison of costs and GHG emission of the developed hybrid treatment process with the conventional hybrid treatment system and aerobic treatment system used for the treatment of CTMP pulp and paper wastewater. The GoldSET software (Golder Associates, Montreal, Quebec) was applied to evaluate the sustainability of the developed process through comparison with other treatment processes.

2 GHG GENERATION AND COST ANALYSIS

Cost estimation and GHG analysis is carried out for the conventional hybrid treatment (system A), aerobic treatment (system B), and the developed hybrid treatment (system C) processes. Based on the effect of wastewater saturation with CO_2 on GHG emission and cost, the feasibility of the developed process (system C) will be investigated. The costs and GHG emissions associated with the developed process are assumed to be the sum of costs and GHG emission from the conventional hybrid treatment system (system A) and costs and emission offsets by applying the scrubber.

Table 1 shows GHG emissions and costs of the three different systems examined in the present work. The anaerobic treatment alone was not considered as a treatment option because pulp and paper wastewater is usually a high strength wastewater and anaerobic treatment alone cannot meet the discharge standards (Buyukkamaci and Koken 2010). However, the presence of anaerobic and aerobic reactors in the hybrid treatment process benefits from the specific advantages of anaerobic treatment such as methane generation, lower energy requirements and sludge production (Shihwu Sung 2008).

Table 1: Treatment systems analyzed based on their GHG emissions and cost

Process design	Main treatment	Second treatment	Tertiary treatment	Nitrogen removal	Solid treatment	CO_2 scrubber
System A	Anaerobic	Aerobic	No	No	Landfill	No
System B	Aerobic	No	No	No	Landfill	No
System C	Anaerobic	Aerobic	No	No	Landfill	Yes

2.1 Case Study

The case study in the present work is based on the operation of Tembec Matane CTMP wastewater treatment plant. Tembec Matane is a producer of high yield pulp and is located on the south shore of the Saint Lawrence River at the mouth of the Matane River in Quebec. It applies hybrid treatment process (system A) to treat the generated wastewater. The Tembec Matane wastewater treatment process consists of a primary clarification process to remove large particles, followed by secondary biological treatment using an anaerobic internal circulator reactor (IC) and an activated sludge reactor.

The flow diagram of the Tembec Matane wastewater treatment plant (WWTP) is shown in Figure 1. The input and output sources of energy are shown in this figure. The GHG and non-GHG emissions are shown in red and black, respectively.

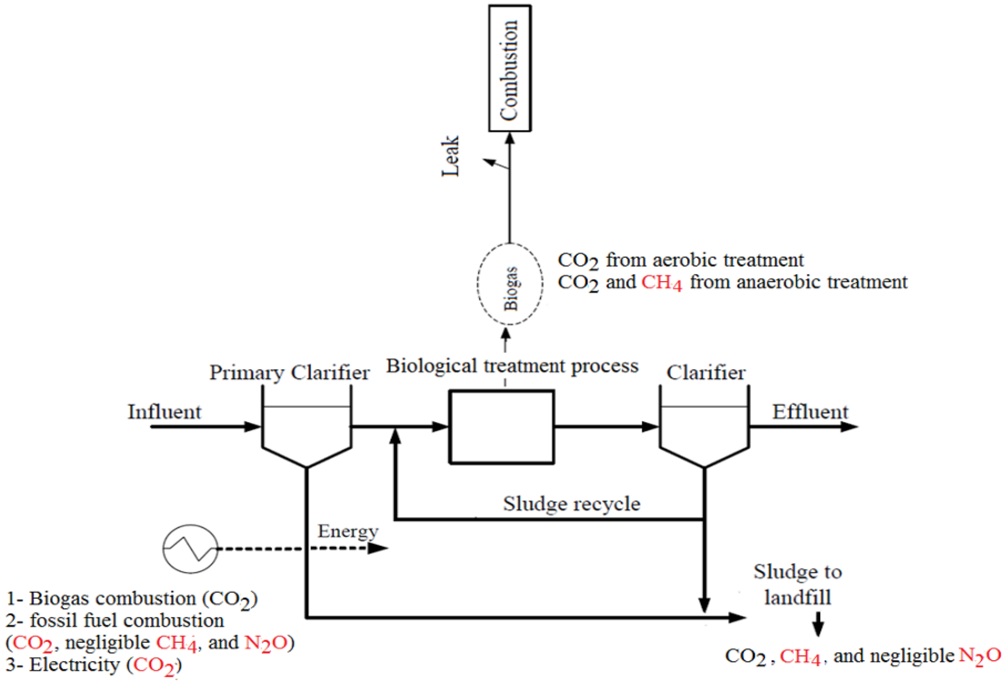


Fig 1: Flow diagram of the examined wastewater treatment system. GHG emissions are shown in red.

The information provided by the Tembec Matane CTMP WWTP is summarized in Table 2.

Table 2: Information from Tembec Matane WWTP

	Anaerobic	**Aerobic**
Capital cost	25 M (^{1*}2012)	10M (^{2*}1989)= 16.45M(2012)
Solid waste produced	230 m^3/month (sold, 100$/ m^3)	4380 dry ton/y (sent to uncovered landfilled)
Recycling of gas	95% (to dry pulp)	NA
CH_4/kg COD removed	0.4 m^3/kg COD removed	NA
CH4 % in biogas	70-75%	NA
COD removal	65%	85% (80% for system B)
BOD removal	85%	≈100% (95% for system B)
Overall power requirement^{3*}	0.01 kW/m^3 reactor volume	1.5 kWh/ kg COD_{rem}
Other information: Energy generation for Tembec Matane pulping plant results in 247 million m^3 CO_2/y emission. Flow, COD and BOD entering the anaerobic digestion are respectively equal to 5 Mm^3/y, 10.2 and 4.8 g/l.		

1*Annual index for 2012= 584.6 (Web 2)
2*Annual index for 1989= 355.4, (Brown 2007)
3* Keller and Hartley (2003)

The assumptions made based on literature review during the estimation of GHG emission and cost are presented in Table 3:

Table 3: List of assumptions

Off-site sources of GHG emissions are ignored to simplify the comparison
For the estimation of GHG emission from landfills, a simplified first order decay approach is used, which is the default method recommended by the IPCC (IPCC 2000a)
CO_2 production during power generation is assumed to be 0.96 kg CO_2/kWh (Cakir and Stenstrom 2005; Keller and Hartley 2003)
CO_2 production during biological treatment is assumed to be 1.19 g CO_2/g BOD removal (calculated based on information from Rittmann and McCarty 2001 and Bani Shahabadi et al. 2010)
The growth yield coefficient of activated sludge is 0.5 kg dry activated sludge / kg removed BOD (Liu, 2003; Wei et al., 2003).
CO_2 content of the flue exhaust gas is equal to 60%
The only GHG emission reported from landfills belongs to CH_4. The generation of N_2O is negligible and CO_2 is part of the carbon cycle in nature (NCASI 2005)
CO_2 emission from biological treatment is carbon neutral (not GHG) and N_2O emission is negligible
95% of biogas from anaerobic reactor is recovered (not GHG) and 5% leakage to the atmosphere (GHG)
CO_2 emission from the combustion of recovered methane is not GHG
Energy requirement for biological treatment and scrubber operation in system A and C is provided by the combustion of recovered methane. Therefore the CO_2 generation from power generation is not GHG.
Carbon offset sources: • recovery of methane and prevention of its entrance to the atmosphere • combustion of recovered methane and its use instead of fossil fuel as an energy source • bioconversion of dissolved CO_2 (as a result of applying scrubber) to methane
The assumed costs and values: • Carbon Credit (CC): U.S. $ 6.50 / ton CO_2e (Topo Geo 2012). • Light crude oil: 0.550$/l (Web 3) • Electricity generation: 0.125$/kWh (Hydro Quebec 2013) • Sludge disposal: 17$/$m^3$ (Buyukkamaci and Koken 2010)

2.2 Greenhouse Gas Analysis

The types and magnitude of GHG emissions from WWTPs depend on the applied treatment methods. In the pulp and paper industry, the GHG emissions consist of CO_2, methane and nitrous oxide. Other emissions are negligible. The sources of GHG emissions in WWTPs are classified as on-site and off-site emission sources. The on-site GHG emissions originate from the WWTPs due to biological treatment, energy production and sludge treatment. Off-site GHG emissions are related to the production and transmission of fuels and chemicals for on-site use, as well as off-site generation of electricity (Yerushalmi et al., 2013).

To calculate the total GHG emission from WWTPs, the Global Warming Potential (GWP) based on 100-year horizon is used in the calculations in which 1 g methane and 1 g nitrous oxide are equal to 21 and 310 g CO_2e, respectively (IPCC, 2007). Based on assumptions in Table 3 and data from Table 2, the three treatment systems in the present work are compared in Table 4 for their corresponding GHG emissions and energy requirements, where GHG emissions are shown in red.

Table 4: Summary of GHG generation and energy consumption for systems A, B, and C

	System A	**System B**	**System C**
Energy requirement (M kWh/y)	15.5	60.7	15.7
CO_2 emission from energy generation (tCO_2/y)	14,933	58,265	15,107
CH_4 generation in anaerobic reactor (Mm^3 CH_4/y)	13.2	-	13.4 to 18.7
5% CH_4 leakage from the anaerobic reactor (tCO_2e/y)	9113	-	9,300 to 12,900
95% CH_4 recovery from the anaerobic reactor (tCO_2e/y)	173,150	-	176,740 to 245,000
Energy equivalent of recovered methane combustion (M kWh/y)	115	-	117 to 162
Saving in light oil by combustion of recovered methane (M l oil/y)	11.8	-	12 to 16.7
Revenue of saved light oil by methane recovery (M$/y)	6.5	-	6.6-9.2
CO_2 emission from combustion of the recovered CH_4 (tCO_2/y)	110,000	-	112,680 to 156,000
CO_2 emission from anaerobic reactor (tCO_2/y)	8,680	-	8,680
CH_4 emission from landfilling of aerobic reactor sludge (tCO_2e/y)	4,250	11,359	4,250
CO_2 emission from aerobic reactor (tCO_2/y)	4,400	27,900	4,400
Carbon credit (M$/y)	1.28	0	1.34 to 1.92
Carbon offset (tCO_2e/y)	196,191	0	206,108 to 294,994
Total GHG emission (tCO_2e/y)	13,360	69624	13,550 to 17,150
Total not GHG emissions (tCO_2e/y)	28,010	27,900	28,190

The advantages of scrubber application in the developed hybrid treatment are summarized in Table 5.

Table 5: Advantages of using spray scrubber in system C

Feature	**Value**
Carbon offset by applying a scrubber (tCO_2/y)	496 to 9,912
Carbon credit for the carbon offset by applying a scrubber ($/y)	3,220 to 64,430
Excess methane generation from anaerobic reactor as a result of applying a scrubber (m^3 CH_4/y)	273,000 to 5,461,000
Increase in methane generation in developed system compared to conventional Hybrid treatment system	From 2 to 41%
Energy equivalent of the excess recycled methane combustion (M kWh/y)	2.4 to 47.5
Savings in light oil fuel consumption by combustion of excess recovered methane from anaerobic reactor (M L oil/y)	0.24 to 4.9

2.3 Cost Analysis

Cost analysis is carried out to predict if the project is economically feasible for capital investment. In this section, the costs and revenues to the plant from each of the three examined systems are compared by using assumptions presented in Table 3. The total cost is the summation of capital cost, operational and maintenance costs.

The costs for application of the scrubber are estimated based on the EPA fact sheet (2002) and the results are summarized in Table 6. The operation costs of the scrubber decrease as the volume of processed gas increases. The maintenance cost, on the other hand, decreases based on the liquid type. If the liquid has very fine particles that do not clog the nozzles, the maintenance costs are much lower. In the Tembec Matane case study, the CTMP wastewater has very fine particles and a large amount of gas passes annually through the scrubber which decreases the operation and maintenance costs. It is not surprising that by applying the scrubber, the maintenance cost is a considerable portion of the costs.

Table 6: Cost of applying a spray scrubber for the case study

Capital cost	$276770 ($10 per scfm)
Operation and maintenance cost	$415155 (22599$ assumed for operational cost, which leaves $392556 for maintenance cost) annually, ($15 per scfm)
Annualized cost	$424381 ($15.33 per scfm)
Life time	30 years (the same as anaerobic treatment life time)

The summary of results of cost estimation for systems A, B and C is presented in Figure 2. Figure 2 shows that despite the higher capital cost for hybrid treatment systems (system A and C) compared to aerobic treatment process (system B), the total costs would be cheaper. Moreover, a high savings by the combustion of recovered methane instead of fossil fuels is achieved in systems A and C. In system C, the carbon offset by applying a scrubber brings additional revenue compared to system A.

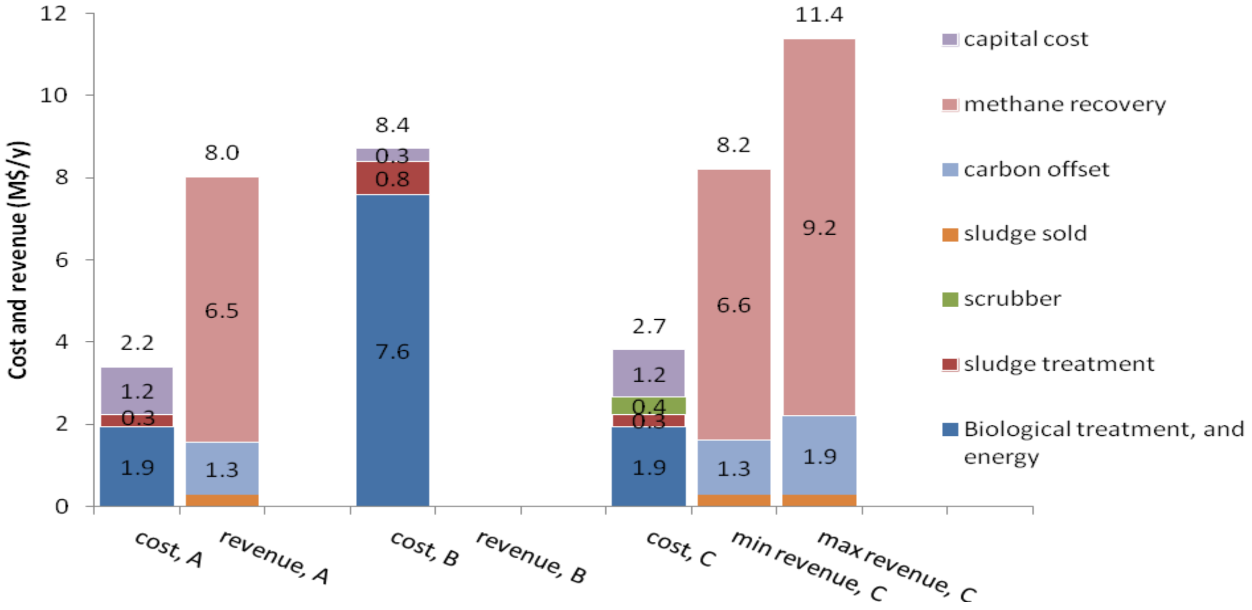


Figure 2: Summary of cost analysis for systems A, B and C

3 GoldSET^{TM} SOFTWARE

The GoldSET^{TM} software, developed by Golder Associates to improve sustainability principles, was used to compare various treatment methods based on their corresponding economical, environmental and social aspects.

"GoldSET is a multi-criteria decision analysis tool that integrates the environmental, social and economic dimensions of sustainable development (SD) into alternative analyses. The tool was specifically developed to embed sustainable development principles using a number of key indicators and variables into projects, and it can summarize interactions of sustainability analyses in easy-to-understand graphic formats" (GoldSET manual guide 2011).

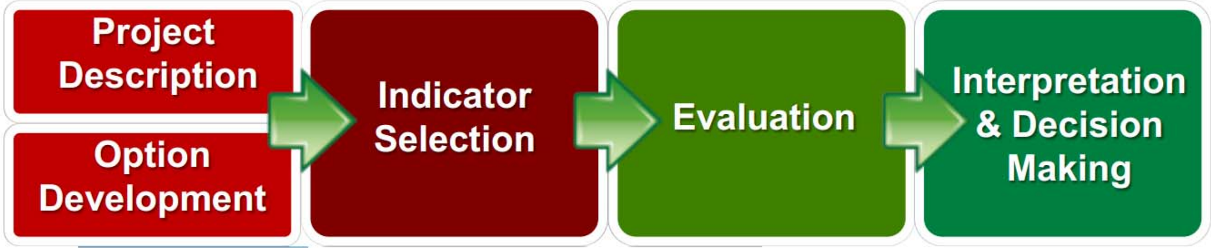


Fig. 3:GoldSET evaluation process (GoldSET manual guide 2011)

The GoldSET software has a 5-Step Evaluation Process as shown in Figure 3. They are:

1. Project Description: The project objectives are specified

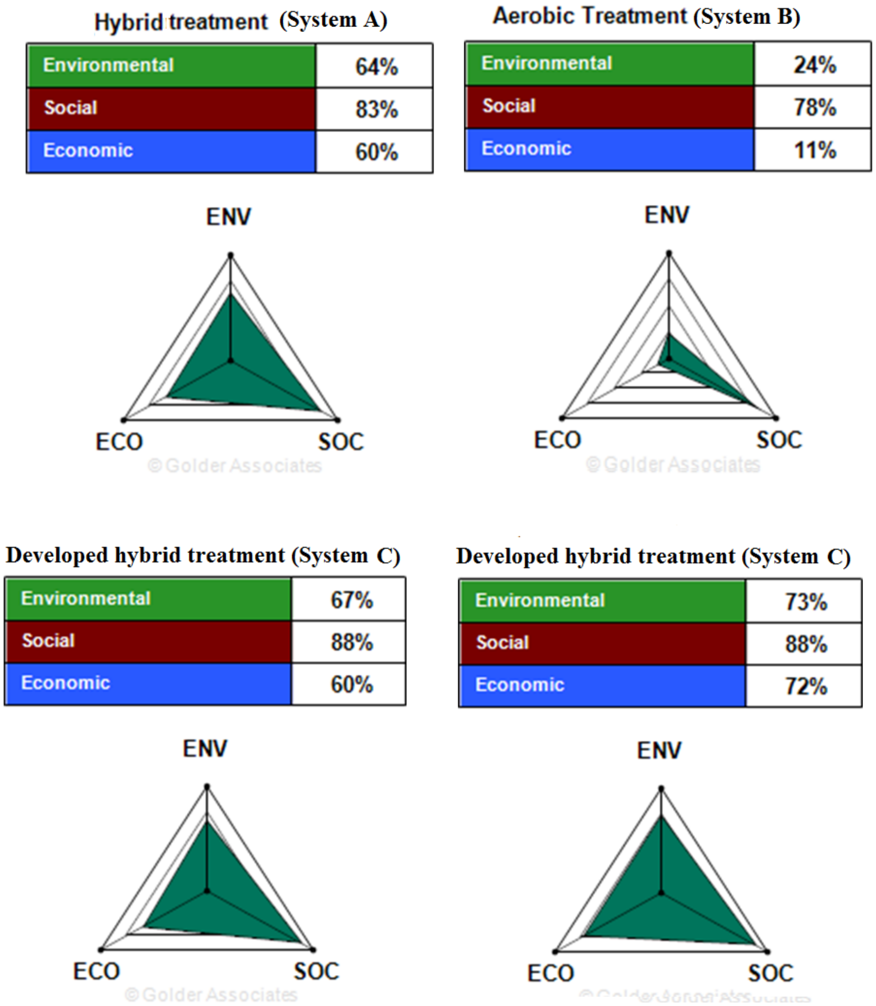
2. Option development: Lists all scenarios that should be compared

3. Indicator Selection: Indicators are subjects that affect the overall performance of the project. A set of indicators are selected from the standard set of indicators in the software for wastewater treatment. An option is available to add or edit indicators according to project specificities. Selected indicators are then weighted to reflect their relative importance to the project.

4. Evaluation: Consists of qualitative and quantitative evaluation of the indicator which helps the ranking of options.

5. Interpretation & Decision Making: Performance of all options under consideration is compared graphically and numerically. In the results summary, a sustainability triangle is designed to show the performance in which each dimension shows one aspect of sustainability (Environmental, social, and economical dimensions). The most sustainable approach and the most suitable technology is the biggest and most balanced triangle with the highest performance in each dimension (Chalise, 2014).

The summary of results obtained from the application of GoldSET software results is presented in Figure 4. In this figure the three systems in the present project are compared based on sustainability features (environmental, social, and economical features). For system C, there is a range of results based on liquid flow rates passing through the scrubber which is equal to 1 to 20 gal/1000 ft^3 gas passing through the scrubber. Consequently, the results are shown in two graphs related to the minimum and maximum numbers. Maximum numbers are achieved when higher liquid flow rates pass through the scrubber. From Figure 4, higher values and a higher balance of environmental, social, and economical aspects of sustainability belong to the developed hybrid process (system C), indicating the high sustainability of this treatment method. Also, the results show the advantage of applying hybrid treatment over aerobic treatment for the treatment of CTMP pulp and paper wastewater.



Hybrid treatment (System A)

Environmental	64%
Social	83%
Economic	60%

Aerobic Treatment (System B)

Environmental	24%
Social	78%
Economic	11%

Developed hybrid treatment (System C)

Environmental	67%
Social	88%
Economic	60%

Developed hybrid treatment (System C)

Environmental	73%
Social	88%
Economic	72%

Figure 4: Summary of the GoldSET software results

4 CONCLUSIONS

GHG emission and overall cost of a developed hybrid wastewater treatment system were compared with those of conventional aerobic and hybrid treatment processes. The developed hybrid wastewater treatment system uses a spray scrubber for the saturation of wastewater with CO_2 before entering the anaerobic reactor. The results showed the advantage of applying hybrid over aerobic treatment.

The addition of CO_2 in the developed hybrid treatment process (compared to conventional hybrid treatment process), increases methane generation by 2 to 41, depending on the volume of wastewater in contact with the gas in the scrubber (These values respectively correspond to 1 to 20 gal liquid/1000 ft^3

gas passing through the scrubber). The suggested process increases methane generation by 273057 to 5461145 m^3 CH_4/y compared to conventional hybrid treatment process. The increase in methane generation will in turn increase the potential recovery of methane which will increase energy generation through its combustion, thus producing higher revenue for the plant. Power generation from the combustion of recovered methane in both systems A and C was more than the required power for the treatment process. Besides, CO_2 emission from the combustion of recovered methane for power generation is not considered as a GHG.

The annual cost and revenue of the developed hybrid treatment system was estimated to be 2.7 and 8.2 to 11.4 M$/y, while the corresponding values for the conventional hybrid treatment system was equal to 2.2 and 8M$/y. Aerobic treatment, on the other hand brings no revenue for the treatment plant and has 8.4M$/y cost for the treatment plant. The approximate GHG offset by the developed hybrid treatment, conventional hybrid treatment and aerobic treatment process respectively was equal to 206000 to 295000, 196000 and zero tCO_2e/y. By comparing the conventional hybrid treatment system with the developed hybrid process with respect to GHG emission and cost, it can be concluded that applying a scrubber for the saturation of wastewater with CO_2 is a promising method, especially when higher liquid flow rates can pass through the scrubber. It can annually save up to 3 million dollars in annual costs of treatment plants and will reduce GHG emissions by 100,000 tCO_2e/y. The results of GoldSET software confirmed the higher sustainability of the developed hybrid treatment process.

5 ACKNOWLEDGEMENTS

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