LIFE CYCLE COMPARISON OF TWO RO CONCENTRATE REDUCTION TECHNOLOGIES

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Abstract. Desalination and water reuse technologies are critical for solving water problems. Unlocking water resources through the minimization of reverse osmosis (RO) concentrate volume offers sustainable opportunities to meet the challenge. A pellet softening lime intermediate concentrate chemical stabilization (ICCS) reactor and a conventional lime softening ICCS for the treatment of RO concentrate were evaluated. Process performance, footprint, chemical usage, energy consumption, residual volume and dewatering characteristics for the conventional and pellet softening ICCS were compared.

To evaluate the overall environmental impact of the two ICCS, a process based Life Cycle Assessment (LCA) was performed for the conventional and pellet softening ICCS technologies. The LCA quantifies the resource and energy needs and wastes generation through the process' life from raw material acquisition to production, use, and disposal. It is based on careful energy and materials balances for all stages. The LCA factored resource inputs (minerals, fossil fuels, land use, etc.) and environmental outputs (damage to natural resources, ecosystem quality and human health, air emissions, toxicity-weighting, global warming potential, ozone depletion potential, eutrophication potential, etc.). This paper will present a comprehensive comparison of the two ICCS technologies including pilot testing results and LCA.

INTRODUCTION

Life cycle assessment (Friedrich) method is a tool which can quantify and compare environmental impacts of the different water treatment systems. "LCA is a technique for assessing the environmental aspects and potential impacts associated with a product (American National Standard Institution)." This method studies a product's entire life (cradle-to-grave) from raw material through production, use and disposal. LCA can assist in decision-making, improving the environmental aspects of products and selection of relevant indicators of environmental performance.

Peters and Rouse (2005) compared three water supply options in South Australian. Stokes and Horvath (2006) used LCA method to study three supply alternatives (importing, recycling, and desalinating) in two site water systems. Energy usage is an important part in water supply system. Stokes and Horvath (2009) researched the energy and air emission of water supply systems for the typically sized U.S. conditions in southern California. They indicated that "energy production was a significant contributor to the overall results for all water sources. In the operation phase, energy production and water treatment chemicals dominated the life-cycle results." Other researches also indicated that (Friedrich et al. 2010; Ortiz et al. 2007; Tangsubkul et al. 2005; Vince et al. 2008) the energy usage was the main source of environmental impacts in their LCA studies.

Research scope and methodology. An LCA methodology or LCA software such as SimaPro has been made according to the ISO standard. An LCA study consists of four steps: 1) Defining the goal and scope of the study, 2) Life cycle inventory (LCI) stage: Making a model of the product life cycle with all the environmental inflows and outflows, 3) Life cycle impact assessment (LCIA) stage: Understanding the environmental relevance of all the inflows and outflows, 4) The interpretation of the study.

In this research, an LCA was performed using SimaPro 7.2 for the two conceptual brackish groundwater desalination facilities. The purpose of the LCA is to extend the comparison of two alternatives to consider environmental impacts associated with the concentrate management processes. The two options being evaluated are: 1) Dual RO with Conventional Lime ICCS and 2) Dual RO with Pelletized Lime ICCS

The conceptual facility produces 10-mgd finished water through partial stream desalination and blending to meet finished water target TDS of 700 mg/L.

The LCA model was specifically developed for the conceptual desalination facility options. The boundaries of the LCA model cover the entire desalination facility using dual RO systems and ICCS facilities including residuals handling, pretreatment, and post-treatment. It includes the groundwater pumping operation and the finished water distribution pumping. However, the construction of the well and the distribution system are excluded. The LCA model includes the disposal of residuals at municipal and industrial landfills for lime sludge, pelletized residual, used cartridges and membranes, etc. The secondary RO concentrate was assumed to be disposed of at evaporation ponds.

Life cycle inventory (LCI). In the LCI stage, each process is built up with quantitative input and output. The process inputs can be divided into environmental input (raw materials and energy resources) and economic input (products, semi-finished products or energy from technosphere).

Input data is collected from the operation record of the pilot system. Based on the available time and budget, data collection mostly focused on the operating stage. The capital and construction data are adopted from the databases. Whenever possible, USA based data was used for the material/process in the LCA inventory analysis. Otherwise, the Ecoinvent database was used for background data such as generic material, energy, transport and waste management. For the foreground data that are particular to this study, the most representative data in Ecoinvent database was used. The database in SimaPro is mostly from cradle to gate. When a process or product is added into another process, SimaPro automatically includes all the relative material flow and environmental load into the target process. Table 1 shows the LCI main data input for the two ICCS options comparison.

Table 1. Life cycle inventory data input summary – conventional and pelletized ICCS

	Quantity[1] (per 10 MG)						
	Conventional lime			Pelletized lime			
Main input categories	60% secondary RO recovery	65% secondary RO recovery	70% secondary RO recovery	50% secondary RO recovery	55% secondary RO recovery	60% secondary RO recovery	Unit
Materials							
Concrete	0.1	0.1	0.1	0.02	0.02	0.02	cubic yard
Steel	19	19	19	13	13	13	lb
Aluminum	$3	$3	$3	--	--	--	USD
Pumps/Blowers /Strainers	$116	$115	$115	$107	$107	$106	USD
Membrane / Cartridge filter Material	35	35	34	36	35	35	lb
FRP/HDPE (Tank Material)	1	1	1	1	1	1	kg
Filter Media	48	47	47	48	48	48	lb
Chemical							
Lime	7	7	7	4	4	4	ton
Sulfuric Acid	3,280	3,255	3,230	3,348	3,321	3,295	lb
Caustic Soda	3,014	3,014	3,014	3,014	3,014	3,014	lb
Sand	--	--	--	4.8	4.8	4.7	ton
Anti-Scalant	295	293	291	301	299	296	lb
Sodium Hypochlorite	1,674	1,674	1,674	1,674	1,674	1,674	lb
Ferric Chloride	--	--	--	373	370	367	lb
Polymer	0.6	0.6	0.6	0.7	0.7	0.7	lb
Energy (Electricity and Fuel)							
Electricity	84,427	83,932	83,444	79,909	79,427	78,952	kW-hr
Transportation	11,955	11,867	11,780	4,965	4,929	4,894	ton-km
Waste							
Inert Waste	38	38	37	38	38	38	lb
Dewatered Solids	63	62	62	2	2	2	Ton
Wasted Pellet	--	--	--	15	15	15	Ton

Notes:

(1) Quantity is daily value over the life span.

(2) Transportation includes chemical delivery and waste solids disposal.

(3) Values presented are averaged to a daily basis assuming producing 10 MG finished water and a facility life cycle of 30 years.

According to Table 1, the pellet softening option requires 80% less concrete and 33% less steel for reactor construction. This can be mainly attributed to the smaller reactor and residuals handling facility. In addition, pellet softening uses approximately 40% less lime and 8% less electricity. Conversely, pellet softening demands for 4.7 tons of sand each day and may require ferric chloride as a filter aid for secondary RO feed pretreatment. Overall, the pellet softening system produces 96% less dewatered solids, but requires 15 ton/day of wasted pellets. This 72% reduction in total solid waste production represents significant savings in the transportation and disposal of solid waste.

Emissions. The LCI output includes a variety of resources consumed and waste emissions to different environmental compartments during the life cycle of the process. It includes raw material, airborne emission, waterborne emission, final waste flow, emission to soil, non-material emission, social issues, and economic issues. In this study, the emissions to air, water, and soil are the focus of environmental concerns. Figures 1, 2, and 3 present the comparison of LCI results on major emissions for conventional and pelletized ICCS. The LCI results are characterized to produce a number of impact category indicators to perform life cycle impact assessment.

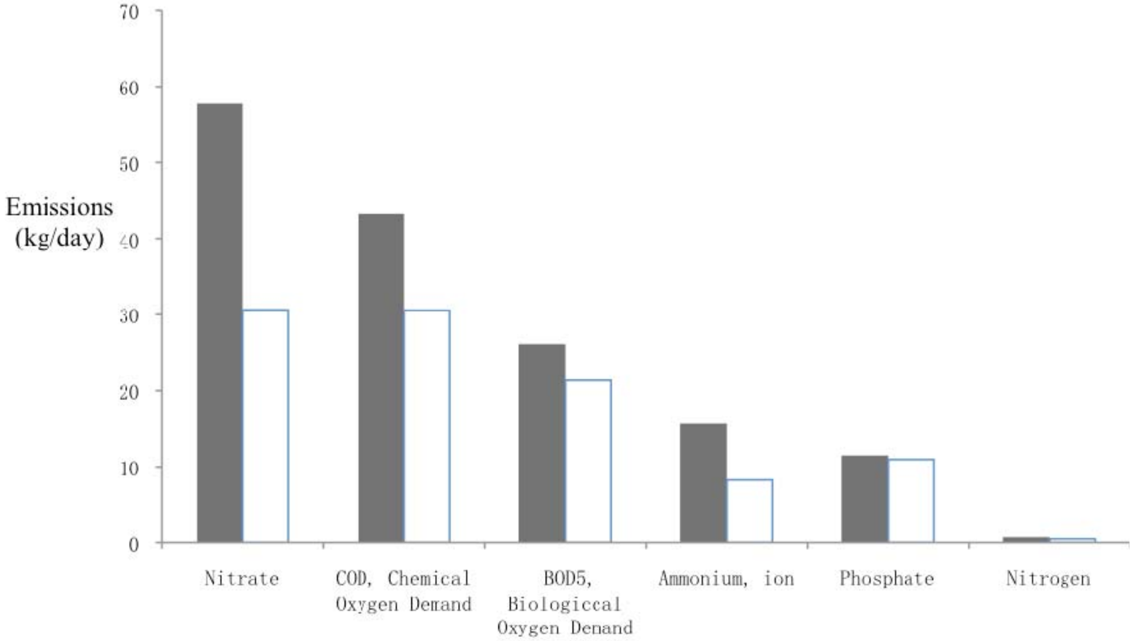

Figure 1: Waterborne Emission - Conventional versus Pelletized Lime ICCS

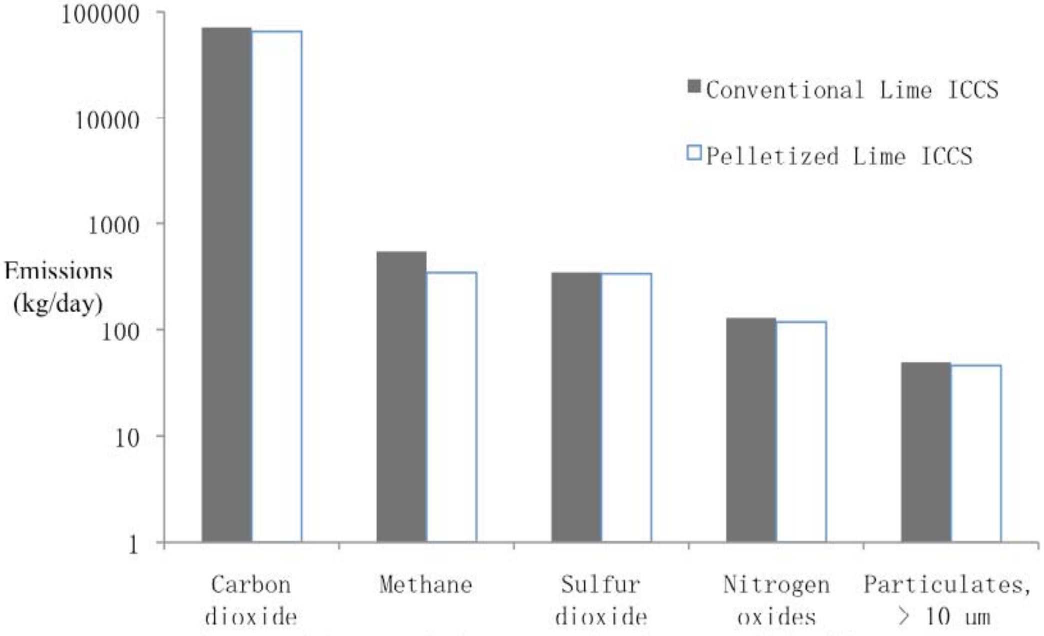

Figure 2: Airborne emission - conventional versus pelletized lime ICCS

The actual emissions to water inventory include 835 substances. Figure 1 shows the top six substances. The pellet system outperforms the conventional systems in all water emission categories. In particular, the emission of nitrate and ammonium from pellet system is approximately 46% and 47% less than that from conventional softening system.

The airborne emission inventory contains 1066 substances and the top five emitted are: carbon dioxide, methane, sulfur dioxide, nitrogen oxides and particulates larger than 10 µm. The two options are comparable in terms of the top 4 air emission, however, the pellet softening system emits approximately 7% less CO2 and 37% less methane.

Emission to the soil compartment contains 525 substances. Figure 3 shows the top 5 in terms of quantity. The two options are comparable in the soil emission. Please be advised that the inert waste (sand) was not counted as emission to soil.

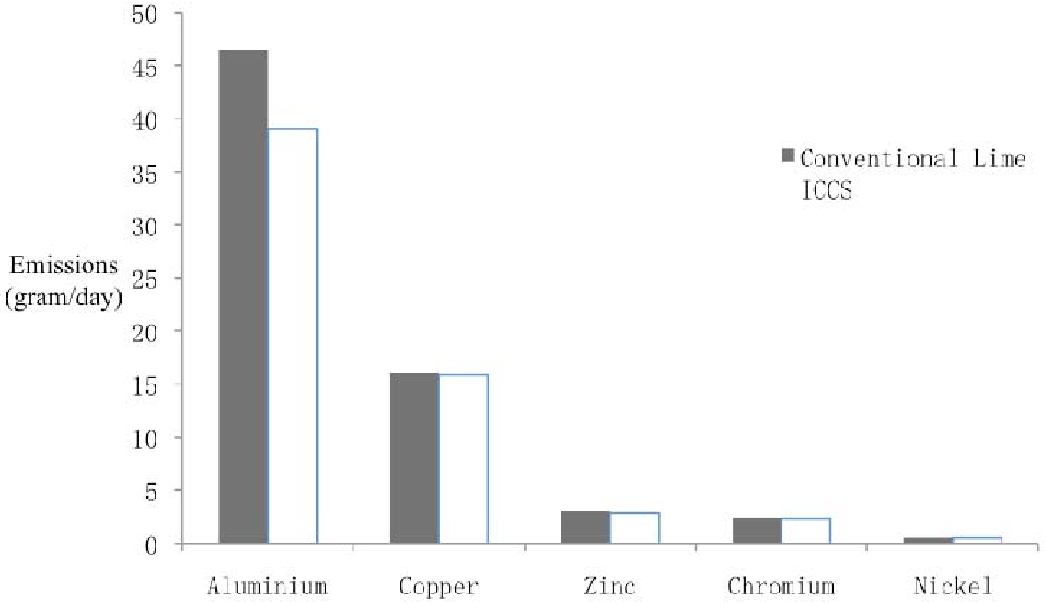

Figure 3: Soil emission - conventional versus pelletized lime ICCS

Life cycle impact assessment (LCIA). Life cycle impact assessment relates the environmental emission inventory with it is disturbance or damage. An LCIA essentially follows two methods: problem-oriented methods (mid points) and damage-oriented methods (end points).

In the problem-oriented approaches, flows are classified into environmental themes to which they contribute. Discharged pollutants were distributed into different environmental media and their contributions were quantified and represented by equivalent units. Themes covered in present LCIA methods and units are: climate change (kg CO2 equivalents), ozone depletion (kg CFC-11 equivalents), Eutrophication (kg N equivalents), acidification (kg SO2 equivalents), respiratory inorganics (kg PM10 equivalents), human toxicity (kg 1,4-dichlorobenzene equivalents) ecotoxicity (kg 1,4-dichlorobenzene equivalents), and, more recently nonrenewable energy (MJ primary energy). The actual selection of themes varies from methods to methods. The midpoint methods simplify the complexity of hundreds of flows into a few environmental areas of interest, yet sometimes were still hard to communicate and compare results of several options of a product/system. The damage-oriented (end points) methods further consolidate the themes into damage to human health, ecosystem health, and resources. For example, the ozone depletion may cause skin cancer thus contribute to the damage to human health.

Among the present LCIA methods, BEES and TRACI are the two methods developed in the US. TRACI is the first LCIA methods in US developed by US Environmental Protection Agency. It is adapted for the U.S. local conditions and models eutrophication very well. However, it is an older model that lacks a few impact categories and uses an older toxicity model. BEES was developed by the National Institute of Standards and Technology based on TRACI. It uses both midpoint and endpoint methods and include categories that are recently gaining public attention, such as indoor air quality and water resource consumption. In this study, the BEES V4.0 method was used to better reflect the conditions at U.S. This method includes thirteen mid-point categories: global warming, acidification, human health (HH) cancer, HH noncancerous, HH criteria air pollutants, eutrophication, ecotoxicity, smog, natural resource depletion, indoor air quality, habitat alternation, water intake, and ozone depletion.

The life cycle impact assessment was performed in two parts: 1) comparing the whole facility impact of the treatment train using conventional softening versus pellet softening; 2) comparing the softening process only.

Table 2 summarizes the overall life cycle environmental impacts of the two facilities divided into different unit process. Overall, the facilities impact significantly to the following categories: global warming, acidification, human health noncancerous, and water intake. The impacts are moderate to human health cancer, human health criteria pollutants, eutrophication, ecotoxicity, smog, and, natural resource depletion. The impacts on habitat alternation and ozone depletion are negligible.

Table 2. Summary of overall environmental impact

Impact category	Unit		Well pump	Primary RO	ICCS reactor	Post ICCS filter	Secondary RO	ICCS residuals	Post treatment - disinfection and distribution	Total
Global Warming	g CO2 eq	Conventional	2.16E+07	2.13E+07	5.17E+06	3.90E+03	6.75E+06	1.96E+07	1.60E+07	9.04E+07
		Pellet	2.16E+07	2.13E+07	3.68E+06	3.90E+03	6.75E+06	8.52E+06	1.60E+07	7.78E+07
Acidification	H+ moles eq	Conventional	7.60E+06	8.13E+06	3.49E+05	9.31E+02	2.57E+06	2.38E+06	4.82E+06	2.59E+07
		Pellet	7.60E+06	8.13E+06	4.98E+05	9.31E+02	2.57E+06	6.22E+05	4.81E+06	2.42E+07
Human Health Cancer	g C6H6 eq	Conventional	4.44E+04	4.38E+04	1.54E+03	1.23E+01	1.39E+04	1.13E+05	2.77E+04	2.45E+05
		Pellet	4.44E+04	4.38E+04	2.47E+03	1.23E+01	1.39E+04	6.62E+03	2.76E+04	1.39E+05
Human Health Noncancerous	g C7H7 eq	Conventional	7.57E+07	7.45E+07	4.52E+06	3.49E+04	2.36E+07	2.82E+07	7.01E+07	2.77E+08
		Pellet	7.57E+07	7.45E+07	5.16E+06	3.49E+04	2.36E+07	6.28E+06	6.87E+07	2.54E+08
Human Health Criteria Air Pollutant	micro-DALYs	Conventional	2.56E+03	2.68E+03	1.83E+02	1.17E+00	8.51E+02	6.59E+02	1.64E+03	8.58E+03
		Pellet	2.56E+03	2.68E+03	1.93E+02	1.17E+00	8.51E+02	1.63E+02	1.64E+03	8.09E+03
Eutrophication	g N eq	Conventional	3.10E+04	3.03E+04	6.16E+02	2.12E+01	9.62E+03	5.79E+04	1.92E+04	1.49E+05
		Pellet	3.10E+04	3.03E+04	1.48E+03	2.12E+01	9.62E+03	2.76E+04	2.23E+04	1.22E+05
Ecotoxicity	g 2,4-D eq	Conventional	5.51E+04	5.47E+04	2.58E+03	3.62E+01	1.73E+04	2.06E+04	1.68E+05	3.18E+05
		Pellet	5.51E+04	5.47E+04	3.64E+03	3.62E+01	1.73E+04	6.52E+03	1.61E+05	2.99E+05
Smog	g NOx eq	Conventional	5.03E+04	5.10E+04	5.88E+03	1.40E+01	1.60E+04	2.78E+04	3.43E+04	1.85E+05
		Pellet	5.03E+04	5.10E+04	6.08E+03	1.40E+01	1.60E+04	7.77E+03	3.43E+04	1.65E+05
Natural Resource Depletion	MJ surplus	Conventional	1.45E+04	1.48E+04	3.66E+03	5.76E+00	4.66E+03	5.28E+03	1.03E+04	5.33E+04
		Pellet	1.45E+04	1.48E+04	2.77E+03	5.76E+00	4.66E+03	1.38E+03	1.03E+04	4.85E+04
Habitat Alternation	T&E count	Conventional	4.94E-10	4.81E-10	3.47E-12	2.62E-13	1.53E-10	2.22E-09	2.94E-10	3.65E-09
		Pellet	4.94E-10	4.81E-10	1.88E-11	2.62E-13	1.53E-10	5.48E-10	2.94E-10	1.99E-09
Water Intake	liters	Conventional	8.33E+07	8.14E+07	1.56E+07	1.20E+04	2.59E+07	2.11E+07	6.05E+07	2.88E+08
		Pellet	8.33E+07	8.14E+07	1.14E+07	1.20E+04	2.59E+07	5.57E+06	6.04E+07	2.68E+08
Ozone Depletion	g CFC-11 eq	Conventional	1.71E-01	3.68E-01	4.48E-01	2.57E-04	9.08E-02	1.07E+00	2.88E-01	2.43E+00
		Pellet	1.71E-01	3.67E-01	3.33E-01	2.57E-04	9.08E-02	3.25E-01	2.68E-01	1.56E+00

Figures 4 and 5 present a summary of the impact assessment results, comparing conventional lime ICCS and pelletized lime ICCS. As all impact categories have different units, the comparisons are plotted on a percentage scale to illustrate the magnitude of differences between the two options. For all categories, the enviromental impacts associated with conventional lime ICCS are higher than those of pelletized lime ICCS.

Figure 4 is a comparison based on the entire conceptualized desalination facility (i.e. based on producing 10 MGD finished water). The differences between the two options range from 5% for categories such as acidification or ecotoxicity to 45% for categories such as Human Health Cancer and habitat alteration.

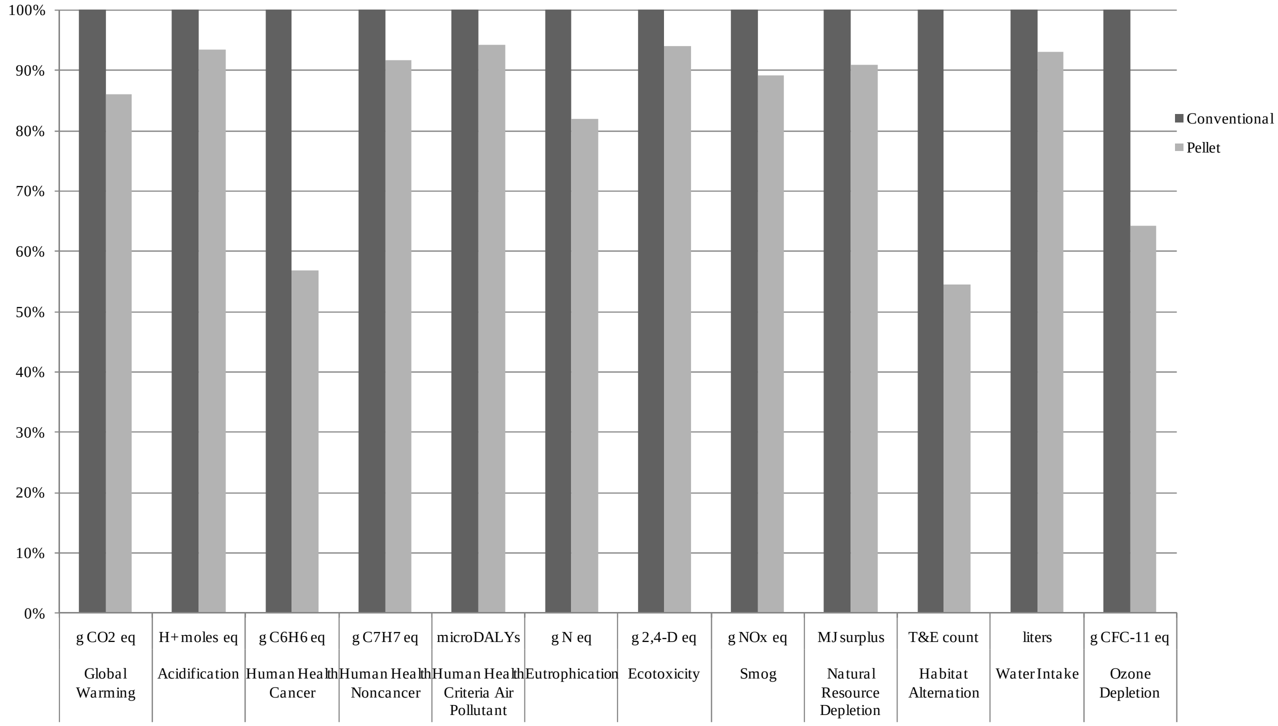

Figure 4: Impact assessment comparison based on the entire facility

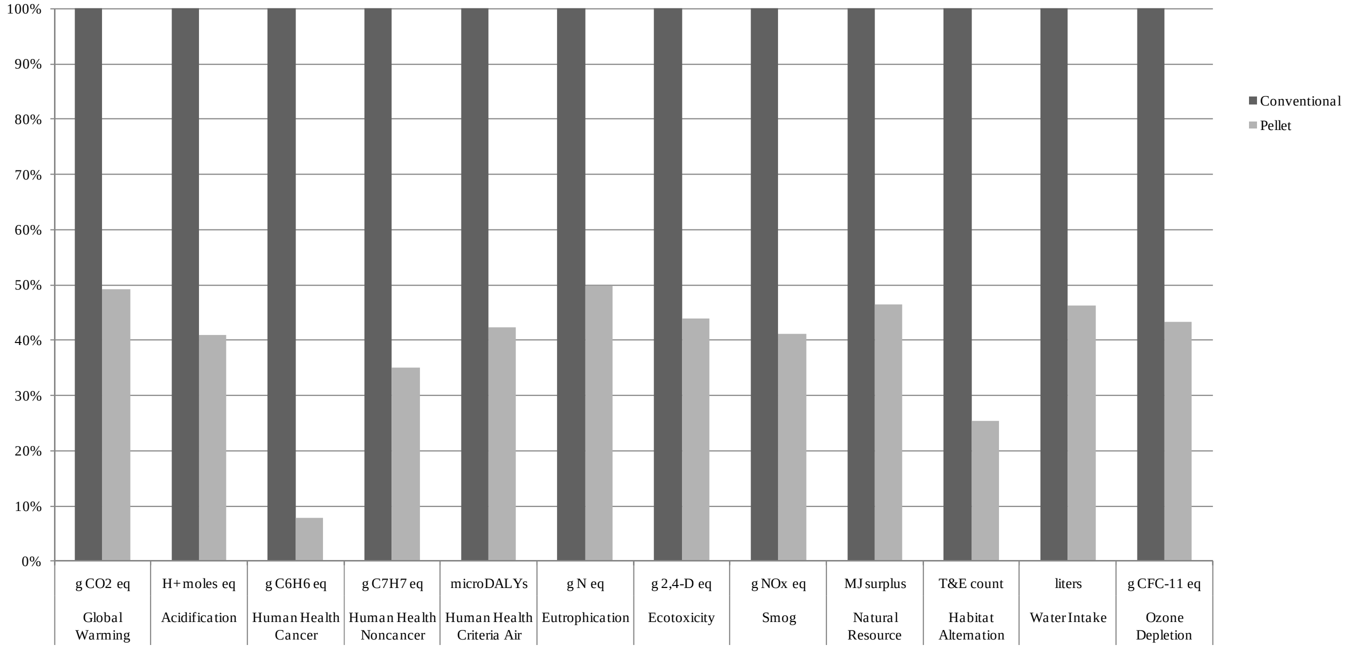

Figure 5: Impact assessment comparison based on ICCS process

Figure 5 is a comparison of the two ICCS process options (i.e. based on producing ~1.16 MGD of filtered and stabilized concentrate, which is the secondary RO feed). In this figure, the differences between the two options are more eminent, ranging from 50% to up to over 90%. The major differences in the human health cancer category can be attributed to the reduced waste disposal.

CONCLUSIONS

During the construction phase, the reduced reactor volume of pellet softening requires less construction materials than the conventional methods of concentrate reduction. During the operation phase, pellet softening uses approximately 40% less lime ($131,400 savings per year) and 8% less electricity ($300,000 per year). Further savings are realized through a 96% reduction in dewatered solids produced, however, it should be noted that 15 tons of pellets are wasted each day. Conversely, pellet softening requires 1700 tons of sand and 67 tons of ferric chloride each year. Overall, the fiscal and environmental savings achieved with pellet softening indicate the potential of the technology.

From a life-cycle point of view, the pellet system outperforms the conventional system in all water emission categories. In particular, the emission of nitrate and ammonium from pellet system are reduced by approximately 46% and 47%, respectively. The two options are comparable in terms of the top 4 air emissions. Due to the decreased electricity consumption, the pellet softening system emits roughly 7% less CO2 and 37% less methane. For all categories, the environmental impacts associated with conventional lime ICCS are higher than those of pelletized lime ICCS. When the environmental impacts of the two ICCS options are compared, the pellet softening option decreases all twelve categories by at least 50%. Significant differences in the human health cancer category can be attributed to the reduction of waste disposal. When these environmental impact reductions are factored into the entire process train each category is reduced by 5-45%.

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