LIFE CYCLE ASSESSMENT OF MEMBRANE BIOREACTOR VERSUS CAS WASTEWATER TREATMENT: MASDAR CITY AND BEYOND

*SANAA PIRANI, LAKSHMI NATARAJAN, ZEINA ABBAS, HASSAN ARAFAT**
Masdar Institute of Science and Technology
P.O. Box 54224, Abu Dhabi, UAE
* Corresponding author, harafat@masdar.ac.ae

ABSTRACT

Wastewater Treatment (WWT) has become compulsory by government regulations in most parts of the world due to the importance of maintaining the sanitation of fresh water and preserving the environment. The processes used to treat waste water generally include pre-treatment and either one or two decantation stages. One tool to assess environmental impacts resulting from shifting from one design choice for WWT to another is by conducting Life Cycle Analysis (LCA) of all considered designs/systems. An LCA study considers all the environmental impacts associated with a product or system throughout its life cycle (i.e., from cradle to grave). In this paper, an LCA study is conducted to compare between two wastewater treatment technologies, namely: Conventional Activated Sludge systems (CAS) and immersed Membrane Bioreactor (MBR) systems. In this effort, a full design of both systems was executed to account for relevant material and energy inventories and environmental impacts.

The comparison starts at the level of a small community, considering the MBR plant in Masdar City (Abu Dhabi, United Arab Emirates) as an example, then scaling up the study to encompass the entire Abu Dhabi emirate. After the LCA, reflections based on the costs of the two wastewater treatment options are made. Moreover, in view of Abu Dhabi's future sustainability targets, variables such as clean energy sources and carbon tax are also considered. The results of this study reveal that MBR treatment is more environmentally friendly than CAS treatment. However, when other parameters are taken into consideration, it is recommended that MBRs be used on a decentralized scale, whereas CAS plants should be used on a larger, more integrated scale.

Keywords: Life cycle assessment (LCA), Wastewater treatment, MBR, WWT

INTRODUCTION

Wastewater is generated mainly by residential, commercial, industrial, and institutional establishments. This wastewater is treated through physical, chemical and biological processes in order to remove contaminants from it so as to produce treated effluent and sludge as a byproduct. The sludge can either be disposed of or reused for agricultural purposes, specifically as fertilizer. As for the treated effluent, it is considered to be environmentally safe and can be used for landscaping purposes or for flushing toilets.

There are several wastewater treatment technologies being implemented, namely: Conventional Activated Sludge Systems (CAS), Conventional Activated Sludge Systems with Filtration Treatment (CAS-TF), immersed Membrane Bioreactor (MBR), and external MBR (Ortiz, Raluy, & Serra, 2007). The CAS process is briefly described as follows: the influent enters a pre-treatment stage (which is where screening of solids takes place), and is then passed through two decantation stages to remove dissolved and suspended biological matter. After that, the stream is passed through a disinfection stage in order to separate as many microorganisms as possible before discharging the effluent into the environment. As for the CAS-TF process, it is a mimic of the CAS process except that instead of having a disinfection stage, it uses ultrafiltration (UF) membranes as part of its tertiary treatment. On the other hand, immersed and external MBRs use the principle of separation by polymeric organic or inorganic membranes rather than using secondary and tertiary treatments (Sutton, 2006). However, the difference between the two is that in the external MBR, the membranes are placed external to the bioreactor whereas in the immersed MBR, the membranes are directly submerged in the bioreactor mixed-liquor (Sutton, 2006). For the purpose of this project, the two technologies chosen to be compared are the CAS process and the immersed MBR process.

This project evolves in three phases: in the first phase, a base case LCA is performed to compare between the environmental impacts of the MBR and CAS plants for Masdar City only. The second phase includes a sensitivity analysis by varying two parameters in the model (energy mix and sludge treatment) and observing their effects on the LCA results. Finally, in the third phase the model has been scaled up for analysis on the Abu Dhabi city level scale. This phase also includes policy recommendations based on the outcomes of the first two phases, communications with experts, simple cost and clean energy sources analysis; and visualizing the impacts of all these policies on the overall LCA outcome. The LCAs performed as part of this project were done with the help of SimaPro, an LCA software designed by PRé Consultants (The Netherlands).

Goal and Scope

The goal of this study was initially to compare two wastewater treatment processes: CAS treatment with Masdar City's Membrane Bioreactor (MBR) treatment process, and to propose the more eco-friendly option. The goal was later expanded to consider wastewater

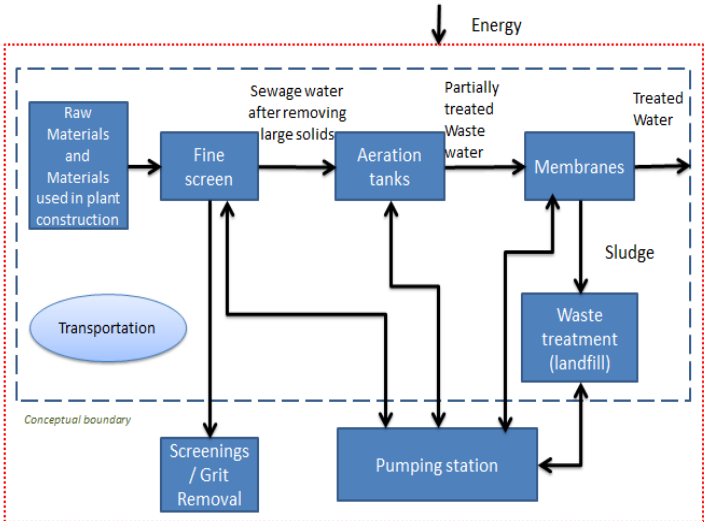


Fig.1: Conceptual Boundaries of the comparative LCA conducted

treatment options for all of Abu Dhabi. Within the scope of the LCA, both the operational requirements and the impact of the capital goods of each system have been considered. The primary stakeholder for this study is the Abu Dhabi municipality since the final aim of the study is to recommend suitable wastewater treatment options for Abu Dhabi.

Clear definitions of the functional unit and the system boundaries were determined. The functional unit chosen in this study is 1 m^3 of treated or processed wastewater. The boundaries of the system define the product stages and processes being considered within the LCA study. **Error! Reference source not found.** shows the block flow diagram of the Masdar City MBR plant, explaining its conceptual boundaries. This is in reference to Phase I of this project. As can be seen, the pumping infrastructure (in terms of its material components) is not part of the conceptual boundary. However, the energy required for pumping, which is the most significant part of the pumping setup, has been considered. The waste from the fine screen is found to be irregular in amount and is relatively negligible, so it has also been excluded from this study. The transportation of the membranes and screens from Hungary (manufacturing country) and also the transportation of sludge to the landfill have been considered. From the plant currently in operation at Masdar City, data over several months was obtained for: the incoming and outgoing water flow rates, the energy consumption, the input chemicals, the COD (Chemical Oxygen Demand) and BOD (Biological Oxygen Demand) values, and the sludge produced. The averages of all these values are considered for this study.
The temporal boundary in this case is the lifetime of the projects which is defined as 25 years. This value was taken as it was found to be a lifetime frequently considered when conducting an LCA for wastewater treatment options (Ortiz, Raluy, & Serra, 2007). The geographical boundaries considered are the UAE and Hungary; the UAE is included because both plants are assumed to be in UAE, and Hungary is considered because some of the equipment for the MBR plant is imported from there. These boundaries come into play when parameters like energy mix, transportation distances etc., are considered.

In Phase III of the study, the analysis has been carried out for a city scale adoption of MBRs as compared to CAS. The boundaries remain the same. The system is just scaled up, and in the case of the MBR, the manufacturers of the parts are assumed to be the same.

Masdar City MBR Plant Description

An immersed MBR sewage treatment plant (STP), which started running in March 2010, was installed in Masdar City in order to treat a peak sewage water volume of 1500 m^3 The products of this plant are: treated water, and bio solids, which are land filled. The main components of the plant are: fine screens, anoxic and aerobic bioreactors, and membrane modules. There are three GE (General Electric) Zenon membrane modules, each with a capacity of 500 m^3.

The raw sewage is first passed through a fine screen which is used to separate solids of diameters greater than 2 mm. Then the stream is passed through anoxic and aerobic bioreactors for de-nitrification and phosphorus removal simultaneously. Following that, the stream is fed into the membrane tank, which contains GE ZeeWeed® membranes, where solid/liquid separation occurs. This membrane process combines the effects of aeration, secondary clarification and tertiary filtration, which makes it more effective and less land occupying than the corresponding CAS process. Waste bio solids are removed after going through a dewatering process whereas the permeate is disinfected and then discharged.

Inventory Analysis and Assumptions

As part of this study, all relevant values were normalized as per the functional unit in order to make the options being considered comparable. Thus, for the different capital goods considered, the total mass is divided by the volume expected to be processed by the plant during its lifetime to give a value with units of mass/m^3, and so on.
Furthermore, another parameter kept constant for all the scenarios investigated was the quality of the water being output by the plants, regardless of whether they were MBRs or CAS plants. Consequently, the BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand) values of the effluent in all cases were the same. This is because the quality of output water is a function of the amount of energy used in the treatment process, since the purer the effluent, the more energy used to process it. Thus this had to be maintained to make the comparison between the options logical. Moreover the quality of the water determines where it can be used. However, this end use has not been considered within the boundaries of the LCA.
It must be remembered that, from the perspective of capital goods, the MBRs considered for all of Abu Dhabi were considered to be larger versions of the Masdar City MBR. All the data used for the Masdar plant was obtained by Masdar Corporate itself as well as GE Power and Water (the manufacturers of the Masdar City MBR

plant), through direct communication with them (Derya, 2011). For all the MBRs, only the main components have been considered, assuming that the effect of considering the smaller parts is not significant. These major parts are the fine screen, the steel tanks, and the membrane cassettes and their housing. The amount of material involved in these parts, and the distance from their point of manufacture to the MBR plant locations in Abu Dhabi, are considered in the calculations.

The membrane material for the Masdar MBR plant is known to be PVDF (Polyvinylidene fluoride) (GE, General Electric Water and Process Technologies - ZeeWeed 500C Cassette Fact Sheet, 2007), and it was therefore also considered to be the membrane material for all Abu Dhabi MBRs. PVDF was not available in the SimaPro databases. It was consequently assumed in SimaPro that the membrane material is cellulose fibers (cellulose acetate) as this material has traditionally been used for desalination membranes (Beardsley, Coker, & Whipple, 1994) and so, it was the closest option available. Such membranes have a life of about three years (DowLiquidSeparations, 1994), and so it is assumed that the membrane would be replaced around eight times during the lifetime of the plant.

The membranes used at the Masdar MBR plant are in the form of hollow weeds which the water flows through. What is more, membranes used in water treatment are usually very thin layers which are supported by another material called the spacer and the two are joined by an adhesive. The material of the spacer was assumed to be polyester (Wagner & Eng, 2001). In addition, it was assumed that the environmental impact of the adhesive between the membrane and the spacer is negligible and it has hence not been considered in the inventory. Moreover, the dimensions of the respective constituents of the membrane units were determined primarily from the fact sheet provided by GE (GE, General Electric Water and Process Technologies - ZeeWeed 500C Module Fact Sheet, 2007).

It is assumed that the only significant emissions are those already built-in in SimaPro as a result of the materials, processes, etc., that have been input.

Finally, land occupation is not being considered as part of this LCA as it is not too much of an issue in the region where the plants are assumed to be located. Also, the dismantling and the final disposal of the plants at the end of their lifetime are considered. This is accounted for by specifying how much of the material of the capital goods is recycled (Selke, 2000).

1. Phase I: Masdar City MBR vs. CAS Treatment of the same capacity grade

Inventory flows are decided according to the system boundaries. As the population of Masdar City grows, so would the volume of water being treated by the MBR. As a result, an increasing flow rate scenario is considered.

Table 1. Maximum Masdar City Flow rate Calculations

Per capita consumption (liters/day)	550
Number of residents	40,000
Total consumption per day (liters)	22000000
Total consumption per day (m^3)	22000

The data obtained from Masdar provided the average flow rates for the MBR plant in 2010 and 2011. The increase in flow was therefore calculated during this time period and it is assumed that this increase would be constant every year until the inflow to the plant reaches that forecasted for a plant serving 40,000 residents (the total number of residents the City is expected to have once it is fully occupied) (Masdar, 2010). This inflow cap was found using current Abu Dhabi water consumption trends (Environment Agency - Abu Dhabi, 2007) and the calculations are shown in

Table 1. It is additionally assumed that the trends followed by the increasing flow are also followed by the energy and chemicals consumed as well as the sludge produced.

However, the parameters mentioned above are not the only parameters that would increase with the increasing flow rate. A larger volume of water being processed by the MBR plant means more MBR units and thus more capital goods. This outlines one of the greatest benefits of MBR technology: that it is available in modular units and so, scaling up is a much easier process.

It is known that the Masdar MBR plant gets its electric energy from the UAE national grid. Currently, 1.7% of the electricity generated by the grid is produced using oil, and the rest is generated with the help of natural gas (IEA, Electricity for United Arab Emirates). 1.7% is most definitely a negligible percentage in such a scenario, and so the electricity needs of the Masdar MBR were assumed as being met by electricity generated from natural gas only.

The design for the CAS plant for this phase was constructed from scratch. This was done using real-time data obtained from Al Wathba Veolia Besix Waste Water treatment plant in Abu Dhabi (Delabie, 2011). The only readymade option used from SimaPro was that referring to the infrastructure of the CAS plants, since this was a parameter that would have less variability depending on the location. This made the CAS scenario quite comparable to the MBR (since their inventories were similarly constructed). Building the inventories from scratch made it possible to trace what various negative impacts were being caused by and provided models which were true to the ground reality in Abu Dhabi.

In the case of the CAS plant, the energy variation form one year to the next was found in literature (Pacific Gas and Electric Company, 2006). The values for the consumption of chemicals and the production of sludge were assumed to be varying proportionally to the flow rate, and their initial values at the beginning of the lifetime were obtained from the data provided by the Al Wathba Veolia Besix Waste Water treatment plant (Delabie, 2011).

The undesired output for both options considered in this phase is sludge. In both types of wastewater treatment it is assumed that this sludge is taken to a landfill. This is as per the information obtained from both the Masdar City MBR plant and the Al Wathba Veolia Besix Waste Water treatment plant. The complete inventory may be found in *Life Cycle Assessment of Membrane Bioreactor Versus* Conventional *Waste Water Treatment: Masdar City and Beyond* (Pirani, Natarajan, & Abbas, 2011).

2. Phase II: Sensitivity Analysis

In the scenarios considered in this phase, the Masdar City MBR case of Phase I was compared to the new scenario as per the parameters being varied.

a. Scenario 1: Abu Dhabi's Current Energy Mix vs. Energy Mix for 2010 - 2035

Abu Dhabi aims to have renewable energy comprise 7% of its installed electricity generation capacity by 2020 (Masdar, 2008). The lifetime considered as part of this project is 25 years, from 2010 to 2035. As a result, it is suitable to consider that the energy powering the Masdar City MBR will also have a renewable energy component. This component was calculated as shown in Table 2, to give the overall percentages shown in Fig. 2.

Table 2. Percentages of renewable energy forecasted to be powering the Masdar City MBR (Renewable Energy World, 2009), (World Nuclear Association, 2011)

ENERGY MIX	Gas	Solar	Nuclear
2010-2020	100	-	-
2020-2030	88	7	5
2030-2035	73	15	12
% of each in lifetime	87	7.3	5.7
Power due to each (kWh)	5.64x10^6	4.76x10^5	3.68x10^5

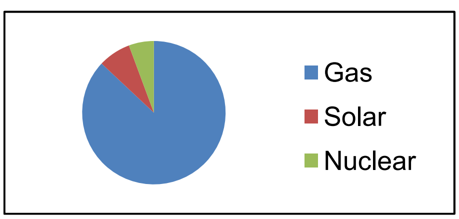


Fig. 2. The overall energy mix considered for 2010-2035.

Generally speaking, using renewable energy instead of fossil fuels would have a positive impact as far as the environment is concerned. However, when taking into account the capital goods that make up the renewable energy plants and their transportation, this is not always the case, and thus this scenario was studied.

b. Scenario 2: Landfilling vs. Composting Sludge

Currently, the sludge produced by the Masdar MBR is landfilled. Therefore, this scenario investigated how the ecological impact would vary if it was composted instead. It was speculated that this measure would cause the environmental impact to decrease, but it was the aim of this activity to find out by how much exactly the situation would improve. It was assumed that the sludge would be taken to Al Ain (Zakher district), where a composting facility exists (The National, 2010).

3. Phase III: MBR vs. CAS Treatment for Abu Dhabi as a Whole

The objective of this phase was to achieve general policy recommendations with respect to MBR and CAS wastewater treatment technologies. It was therefore decided to scale up both types of treatment plants for Abu Dhabi. Both scenarios were treated individually over the 25- year period along with a scenario which had a gradual phasing out of the CAS treatment. The increase in flow rate for the all of Abu Dhabi scenario was determined using Abu Dhabi Water and Electricity Company (ADWEC) statistics (Miller, Al Hajjiri, & Al Hareeri, 2011). These statistics/projections were only available till 2020. Therefore during the 2010-2020 time period, using these statistics the annual flow increase was calculated. This was found to be approximately 5%, and so, this percentage increase was applied from 2020 till 2035.

In the case of the MBR, the increase in energy consumed was found from literature (Radjenović, Matošić, Mijatović, Petrović, & Barceló, 2007). In addition, the consumption of chemicals and the production of sludge were assumed to be varying proportionally to the flow rate.

The CAS plant used in this scenario was similar to that used in Phase I but expanded to be handling the larger flowrates expected for the whole emirate.

Choice of Impact Assessment Method

The Eco-indicator 99 (H) method was used to compare between the two options. This particular method is used extensively in LCAs and is known to be a comprehensive choice that is damage oriented. It reflects "the present state of the art in LCA methodology and application" and "contributions of many LCA experts have been merged" in the EI-99 method (Goedkoop, Effting, & Collignon, 2000). It also has the advantage of being a non-specific method that is easy to use (Gerkens, Teller, Lassaux, & Germain, 2000). The Hierarchist option was used as the possible stakeholders in this LCA are entities such as the Abu Dhabi municipality and therefore the UAE government as well.

Limitations

In any LCA study, assumptions had to be made at different stages. Membranes are the most essential part of the MBR, and in the case of the MBRs being considered in this study, they are actually made from

PVDF material. However, SimaPro software does not have a database for this material. Consequently cellulose fiber was assumed instead. In addition, the study does not consider small parts outside the conceptual boundary defined. For example, the material contribution from the pumping infrastructure could not be considered because of the lack of sufficient data. Also, estimation methods have been used to design the future energy mix and phasing out scenarios as part of sensitivity analysis and are therefore subject to uncertainty. Yet another limitation is that replacements of other equipment besides the membranes have not been considered. At the same time, it must be mentioned that an attempt has been made to include accurate data as far as available and justifiable estimations have been used wherever needed.

RESULTS AND DISCUSSION

1. Phase I: Masdar City MBR vs. CAS Treatment of the same capacity grade

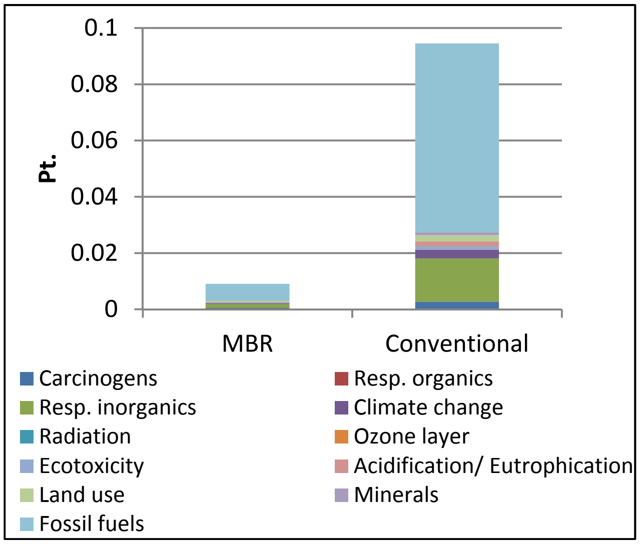


Fig. 3. Single score values of LCA results of Phase I.

The single score result for this phase can be obsered in Fig. 33. It can be seen clearly that the CAS option has a much greater impact on the environment and so is the less favorable option. The greatest source of damage for both the plants is the natural gas which is used to provide the electrical energy for the plants. This is a trend which is found throughout this work, regardless of the scenario being considered. The greater impact of the fuel, relative to other impact categories, in the case of the MBR, is due to the fact that the MBR option uses ultrafiltration which requires greater pumping pressure, making the process more energy intensive.

2. Phase II: Sensitivity Analysis

In this phase, the sensitivity analysis was performed, and in each scenario, the modified version was compared to the MBR plant of Phase I. The complete results of Phase II are shown in Fig. 4, where the MBR plant of Phase I is referred to as the 'MBR-Base'.

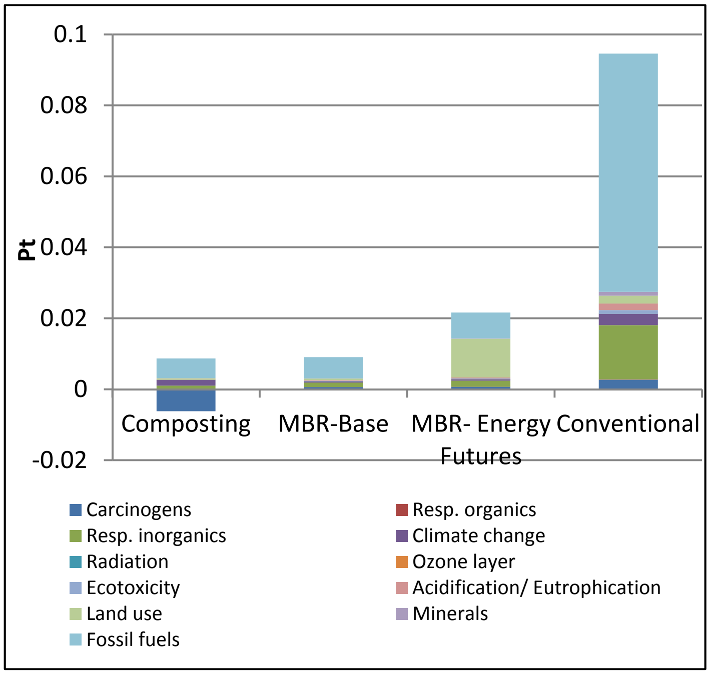


Fig. 4. Single score values of LCA results of Phase I.

a. Scenario 1: Abu Dhabi's Current Energy Mix vs. Energy Mix for 2025 and Beyond

As can be seen from Fig. 4, incorporating renewable energy (RE) sources into the MBR LCA actually made the MBR less environmentally favorable, though it is still more ecofriendly than the CAS option. This may be due to the infrastructure required for providing this renewable energy, especially since the amount of renewable energy being used is very little as a result of the fact that the MBR plant being considered is of small capacity. This is further supported by the fact that the greatest contributor to this negative impact is the 'land use' category. Thus the constructing of RE plants for such minimal power requirements is seen as counterproductive.

b. Scenario 2: Landfilling Sludge vs. Composting Sludge

As can be seen from Fig. 4, a positive impact is the result of composting (which can be seen as a form of recycling). This is obvious from the subzero values of the composting bar in the chart, thereby helping to reduce the overall impact of the scenario.

Fig. 4 also shows the CAS scenario and so it is clear that regardless of the scenario being considered, the MBR is always the more ecofriendly option than the CAS treatment.

3. Phase III: MBR vs. CAS for Abu Dhabi

Error! Reference source not found. displays the LCA results for all the scenarios considered in Phase III. It compares between the CAS and the MBR, both for all of Abu Dhabi. The MBR is found to be 15.73% better than the CAS. Compared to the Phase I results, in this phase there is a much smaller gap between the MBR and CAS treatment technology. This may be because, at the larger effluent amounts being considered in this phase, the plants' material resources are more efficiently used and the technologies benefit from economies of scale. It must be noted that in this case, both the MBR and the CAS plants being considered are at the scale of all of Abu Dhabi, assuming that all of the emirate's wastewater treatment needs would be met by either technology individually.

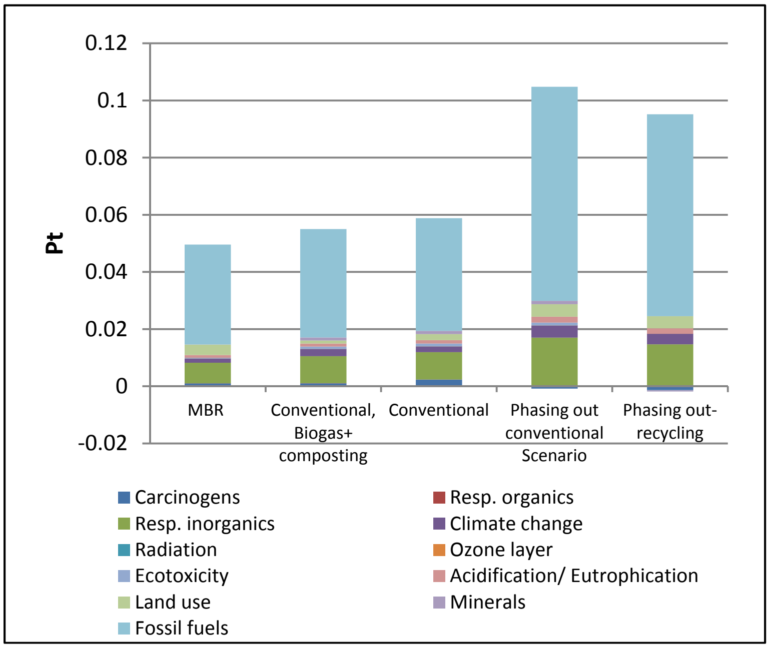


Fig. 5. Single score values of LCA of all scenarios considered in Phase III.

It was learned from Al Wathba Veolia Besix Waste Water plant that their plant produces biogas which is flared off (Delabie, 2011). Thus, in the quest to reach the tipping point between MBR technology and CAS technology, it was assumed in a separate scenario that this biogas was not flared off, but instead, used productively. It was also assumed that the sludge produced was composted. This led to an overall reduction in the ecological impact of the CAS scenario, as is evident from Fig. , and helped to decrease the gap between these two types of wastewater treatment technologies.

Error! Reference source not found. also shows how the phasing out scenario fared from the perspective of environmental impact. In this scenario, there was a gradual phasing out of the CAS treatment, so that in 2010 all of Abu Dhabi's wastewater was assumed to be treated by CAS technology while in 2035 it was all treated by MBR technology. This assumption meant that Abu Dhabi will gradually dismantle existing CAS plants, replacing them with MBR. This phasing out situation ended up being much worse than any other scenario: the MBR for all of Abu Dhabi was 52.33% better, the CAS for all of Abu Dhabi was 43.42% better. Incorporating recycling of the CAS plant (subsequent to its dismantling) into the phasing out scenario only helped to improve it by 10.23%. These adverse results for the phasing out scenario are because it was assumed that, whether or not the CAS plants had reached the end of their lifetime, they were dismantled to make way for the new MBR technology. This lead to an inefficient use of resources and meant that the capital goods were being used for less flow, thus increasing the overall environmental impact. Thus, such a phasing out scenario should not be implemented. Moreover, because of the high quality of MBR effluent, using it for the whole emirate would not be viable since many applications do not require such high quality effluent. This will be discussed later but is mentioned here to emphasize how such a total phasing out situation is unlikely to ever take place in actuality. Nevertheless, these results do help show that a CAS plant should not be taken offline until the end of its lifetime.

Moreover, the scenarios considered in this phase (e.g. MBR technology being used to treat all of Abu Dhabi's wastewater) may be considered to be extreme scenarios, describing the maximum negative environmental impacts possible from each of these situations. Thus, though the scenarios are not likely to become a reality, the results they provide are consequently beneficial in terms of specifying the ecological impact limits for any future situation, regardless of the mix of CAS and MBR technology actually employed.

THE DEVELOPMENT OF A WASTEWATER TREATMENT POLICY FOR ABU DHABI

Clean Energy

As a result of Abu Dhabi's renewable energy targets, it is logical to outline, as part of an Abu Dhabi wastewater treatment policy over the next 25 years, how WWTPs may be powered by clean energy. In addition, from the results shown thus far, it is clear how fossil fuels are the major contributors to the overall negative impact of wastewater treatment technology. Their effect should therefore be mitigated to make the wastewater treatment technology more sustainable. The options being considered in this study are that of using biogas and/or fuel cells to power the plants. These options are being considered as they are already employed efficiently in different parts of the world such as Europe and the US (e.g. King County and Renton, Washington) (Water Environment Research Foundation, 2008).

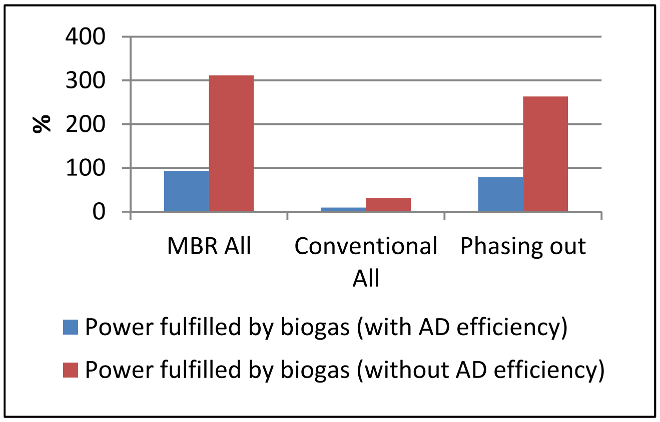
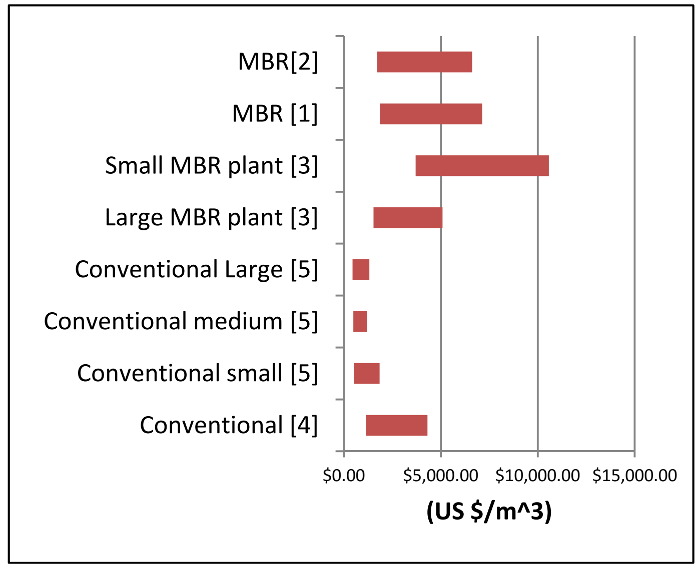


Fig. 5. Biogas a a Plant Energy Source: The potential of sludge to fulfill the energy needs of WWTPs

The biogas is obtained from anaerobic digestion of the sludge produced by the wastewater plants (Monnet, 2003). "The energy potential contained in wastewater and bio solids exceeds by ten times the energy used to treat it," (Reinhardt, 2009) and this is clear from Fig. **5**. The red bars show what percentage of the wastewater treatment plant's energy requirements can be fulfilled by the sludge it produces. This calculation is based on the inherent energy of the sludge produced. However, in actual circumstances, factors like the efficiency of the anaerobic digesters (AD) must be considered (Bracmort & Burns, 2008) and, as a result of that, the blue bars in Fig. 5 are obtained. Generally speaking, MBRs do not produce so much sludge, but the MBR calculations in this project are based on the Masdar City MBR which has started up recently and so is producing more sludge than a plant which has been in efficient operation for many years would be producing. Nevertheless, the potential for biogas to fulfill the energy needs of a wastewater treatment plant is very evident. Using the biogas in this way has the advantages of a smaller carbon footprint, less sludge and lower external energy requirements (Stillwell, Hoppock, & Webber, 2010). What is more, as part of their infrastructure, many wastewater treatment plants already have the setup needed to produce the biogas (United States Environmental Protection Agency, 2011). The biogas produced can be used directly as a source of energy, or additionally, it can be used to fuel new technologies such as fuel cells (Appleby, 1996). Some fuel cells operating on wastewater digester methane produce up to 2 megawatts of electricity (Federal Energy Management Program, 2004).

Cost Analysis

The outcome of the impact assessment showed that the MBR technology has a smaller impact than that of CAS technology. In order to have a holistic picture for policy recommendations, a simple cost analysis was done. The cost analysis mainly consisted of reviewing existing literature concerning cost trends for MBR and CAS treatment options.



References Legend	
1	(EPA, 2008)
2	(Costwater, 2000)
3	(DeCarolis, J. et. al, 2007)
4	(Muga & Mihelcic, 2008)
5	(Costwater, 2000)

Fig. 6. MBR v/s CAS Cost comparison (from Literature)

Fig. 6 shows the cost comparison based on available literature (Costwater, 2000; DeCarolis et al., 2007; EPA, 2008; Muga & Mihelcic, 2008). This chart is for purely indicative purposes. It presents the cost trends for MBRs and CAS plants. It can be seen that MBR plants are much more expensive than CAS plants. Also MBRs benefit significantly from economies of scale. It can be noted that there is a great deal of uncertainty present in the cost of wastewater treatment by MBR. This uncertainty is due to variations in the available literature in forecasted trends in membrane costs, as well as in variations in terms of logistics and most importantly the size of the plants.

The lifecycle costs of MBR technology are based on two main factors- energy consumption and membrane replacement. It was found that the operational costs for both types of plants, apart from the membrane replacement, don't vary significantly. Also MBRs have lower land requirements, and are significantly smaller in size compared to CAS plants of similar capacity, thus requiring smaller infrastructure size and reduced costs of concrete etc.

Carbon Tax

MBR technology is an expensive means to treat wastewater as compared to CAS technology. At the same time, under a stricter environment regime, there could be huge potential savings for MBR.

Error! Reference source not found. Fig. 7 shows the carbon dioxide emissions for the different scenarios. The emissions were obtained in terms of per functional unit from the inventory in SimaPro. The total emissions were then calculated over the lifetime assuming a linear relationship. The error incurred as a result of this assumption is minimized since this margin of error is present for all the scenarios. Moreover, this study is concerned with comparing between the different scenarios on a relative scale. The purpose of this analysis was to indicate the potential carbon savings resulting from the use of MBRs. The price of carbon (i.e. carbon tax) employed in these calculations was taken to be 23 US$ per ton (Lxrichter, 2011). It was assumed that this price is constant throughout the lifetime of the plants, though in reality the price would be set in terms of a market and allowed to vary. It was found that a CAS plant would have to pay roughly 37% more tax than a MBR plant of the same capacity. This shows that a CAS plant is much more carbon intensive as compared to the MBR and though MBR treatment is more expensive than CAS treatment, the environment benefit can be used to offset the cost to a certain extent.

In the UAE, emissions are not taxed in the present policy scheme. However, in a future scenario with international binding contracts, all countries would be liable to reduce their carbon footprint. The probability of such a scenario materializing is very high, and so understanding the potential carbon footprint is a factor that must be considered by decision makers while designing new plants.

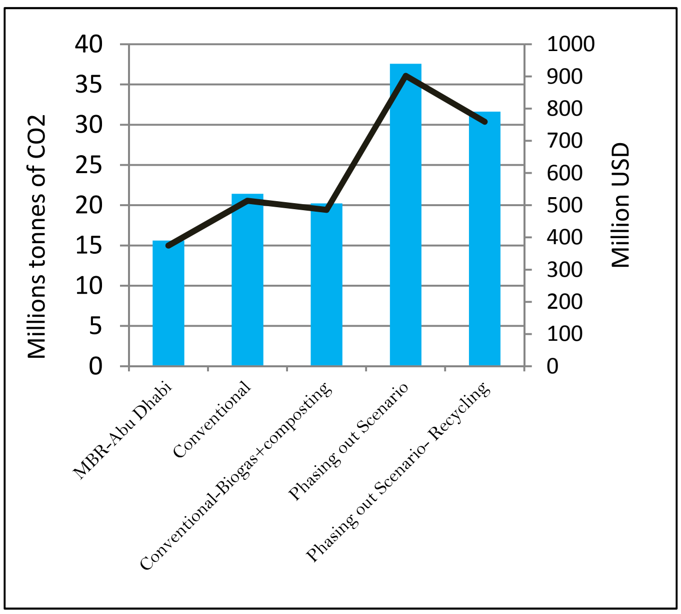


Fig. 7. Carbon dioxide emissions

Existing Water Policy

The water and electricity company in Abu Dhabi were created in 1999 as part of the sector restructuring. The Abu Dhabi Water and Electricity Authority (ADWEA) was consequently formed. In 2000, the Independent Water and Power Producer (IWPP) was formed as a joint venture between ADWEA and a foreign partner (RSB, 2010)

The wastewater sector is governed by Law No (17) of 2005 and Law No (19) of 2007. Under these laws, the following activities are defined for the sector (RSB, 2011):

- Collection of sewage from premises;
- Treatment of the collected wastewater
- Disposal

Currently, there is only one major provider of the full range of wastewater services, namely Abu Dhabi Sewerage Services Company (ADSSC). A number of private companies hold licenses for treating wastewater in Abu Dhabi, but all the treated water is sold to ADSSC. In addition, the government has set standards for the quality of the treated water in addition to standards for pollution control. The treated water is reused for agriculture and landscaping purposes.

It is interesting to note that apart from Masdar City, none of the wastewater treatment facilities in the UAE uses MBR technology alone. This was the motivating factor to understand the reasons for such a diffusion pattern of MBR technology. As part of the policy analysis, several of these plants were contacted to get some insight on practical issues governing technology choice and related decision making.

Field Analysis

Through telecommunication with various entities (Dubai Sewage Treatment plant, GE-Membrane manufacturers and Al Ain Zakher Wastewater Treatment plant) and through research (Stephenson, 2006)&(Melin et al., 2006), the advantages and disadvantages of the MBR process, as compared to the CAS process, have been outlined below. This process has helped to validate the results from the LCA models obtained, as well as to formulate the policy recommendations.

<u>Advantages:</u>

- More eco-friendly than CAS process
- Easy to be installed
- Produces high and more consistent effluent quality
- Can be combined with Reverse Osmosis (RO) to produce potable water
- Benefits from economies of scale
- Small footprint
- Low/zero sludge production
- CAS systems can be retrofit to give MBR units
- Lower sensitivity to contaminant peaks
- Modular/Can be scaled up easily
- More suited for decentralized applications

<u>Disadvantages:</u>

- Significantly more costly to install and operate than CAS
- Pre-treatment is very significant to prevent the common problem of membrane fouling
- High effluent quality not necessary for landscaping and water flushing applications

- Membrane replacement is an issue; frequent membrane monitoring and maintenance
- Higher energy requirements by a maximum of 0.2 kWh/m^3
- Aeration limitations
- Limitations imposed by pressure, temperature, and pH requirements to meet membrane tolerances
- Membranes may be sensitive to some chemicals
- Less efficient oxygen transfer caused by high Mixed Liquor Suspended Solids (MLSS) concentrations
- Treatability of surplus sludge is questionable
- High energy requirement

MBR effluent is of high quality and therefore it is unlikely that it will be used on an entire city scale, since many applications do not require such high quality water. Even MBR manufacturers say that MBRs should only be used where the WWTP needs to be installed quickly or in phases, or where there is limited land availability, or where high quality water output is needed. It might be a good strategy to couple MBRs with Reverse Osmosis plants to produce potable water. Finally, though the CAS process has a higher environmental impact, experts argue that there is potential to make the process less ecologically damaging by targeting individual processes and attempting to optimize them.

CONCLUSIONS

Several conclusions were drawn from this study. In all cases considered, the MBR process has proved to be the more eco-friendly option. However, the environmental impact is not the only parameter that is considered when choosing which treatment process is to be installed. Other parameters needed for judgment include costs, applications for effluent, land availability, and need for additional treatment. In general, the MBR process is used for small scale and decentralized conditions as well as for applications that require high quality effluent while the CAS process is used for large scale applications. CAS plants are cheaper and require less maintenance as compared to MBR plants. However they have a greater environmental impact. MBR plants produce very high quality water. When considering a city wide adoption, high quality water is not required for all applications. In fact, a small proportion of nitrates (which MBRs efficiently remove) could be beneficial when the treated water is used for irrigation. Membrane replacements could produce a significant hassle when being done for extremely large plants. Bearing such practical considerations in mind, it is recommended that MBR technology be adopted for decentralized applications and in industries that require high quality water, and that CAS be adopted for large scale applications, and that efforts be directed to reduce the environmental impact of contributors in the current processes. This is especially because neither renewable energy powering the wastewater treatment processes, nor the total phasing out of the CAS process, are seen as likely scenarios in the short term. Moreover, the CAS plants presently in existence should be allowed to continue operating till the end of their lifetimes. Only then would replacement by MBR technology be a viable option, and even then if the CAS plants can be retrofit to offer MBR treatment, that would help to reduce the impact even further.

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REFERENCES

1. Appleby, A. (1996). Fuel cell technology: Status and future prospects. Energy, 21(7-8), 521–653.
2. Beardsley, S., Coker, S., & Whipple, S. (1994). The economics of reverse osmosis and ion exchange. S. S. Beardsley, S. D. Coker, and S. S. Whipple,, 63–76.
3. Bracmort, K., & Burns, R. (2008). The Use of Anaerobic Digestion Systems to Mitigate Air Emissionsfrom U.S. Livestock Production Facilities. MITIGATING AIR EMISSIONS FROM ANIMAL FEEDING OPERATIONS CONFERENCE proceedings. Retrieved from http://www.ag.iastate.edu/wastemgmt/Mitigation_Conference_proceedings/CD_proceedings/Manure_Storage_Treatment/Bracmort-Anaerobic_Digestion.pdf
4. Costwater. (2000). Total costs for a SBR wastewater treatment plant. *CostWater*. Retrieved December 15, 2011, a from http://www.costwater.com/wastewatertreatment.htm
5. Costwater. (2000). Cost comparison of MBR and SBR. *CostWater*. Retrieved December 15, 2011, b from http://www.costwater.com/membranes/mbr/cost_comparison_of_mbr_sbr.htm
6. Delabie, C. (2011, December). Al Wathba Veolia Besix Waste Water Plant Data. (Z. A. Lakshmi Natarajan, Interviewer)
7. Derya, T. H. (2011, November). Masdar City MBR. (S. I. Pirani, Z. Abbas, & L. Natarajan, Interviewers)
8. DeCarolis, J., Adham, S., Pearce, W. R., Hirani, Z., Lacy, S., & Stephenson, R. (2007). Cost trends of MBR systems for municipal wastewater treatment. Water Environment Federation. Retrieved from http://www.environmental-expert.com/articles/cost-trends-of-mbr-systems-for-municipal-wastewater-treatment-28124/full-article
9. DowLiquidSeparations. (1994). Filmtec Membranes: The Economics of Reverse Osmosis and Ion Exchange. Houston,TX: Watertech Expo.
10. Environment Agency - Abu Dhabi. (2007). Our Roadmap to the Future: Abu Dhabi Environment Strategy 2008-2012. Retrieved from http://www.ead.ae/Tacsoft/FileManager/Misc/EAD%20Strategy%20Eng.pdf
11. EPA. (2008). Wastewater Management Fact Sheet: Membrane Bioreactors. EPA. Retrieved from http://water.epa.gov/scitech/wastetech/upload/2008_01_23_mtb_etfs_membrane-bioreactors.pdf
12. Federal Energy Management Program. (2004, July). Wastewater Treatment Gas to Energy for Federal Facilities - Biomass and Alternative Methane Fuels (BAMF) Super ESPC Program Fact Sheet. U.S Department of Energy: Energy Efficiency and Renewable Energy. Retrieved from http://www1.eere.energy.gov/femp/pdfs/bamf_wastewater.pdf
13. GE Zenon Manuals provided to Masdar Corporate by the manufacturer.
14. GE. (2007, September). General Electric Water and Process Technologies - ZeeWeed 500C Module Fact Sheet.

15. GE. (2007, September). General Electric Water and Process Technologies - ZeeWeed 500C Cassette Fact Sheet.
16. Gerkens, B., Teller, P., Lassaux, S., & Germain, A. (2000). Comparison of two models of environmental valuation - Application to a particular case study (alternative vehicles). LCA Case Studies Symposium.
17. Goedkoop, M., Effting, S., & Collignon, M. (2000). The Eco-indicator 99 - Manual for Designers. http://teclim.ufba.br/jsf/ecodesign/dsgn0212.pdf: Product Ecology Consultants.
18. IEA, I. E. (Electricity for United Arab Emirates). Energy Statisitics. http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=AE.
19. Lxrichter. (2011, November 8). Australia approves US$24 per tonne carbon tax as part of new legislation. *Think Geoenergy*. Retrieved December 16, 2011, from http://thinkgeoenergy.com/archives/9096
20. Masdar. (2008). Abu Dhabi'S MASDAR INITIATIVE breaks ground on carbon-neutral city of the future. Retrieved from http://www.wfes2011.com/uploads/MASDAR.pdf
21. Masdar. (2010). Our Units | Masdar City. Retrieved December 16, 2011, from http://www.masdar.ae/en/Menu/index.aspx?MenuID=48&CatID=27&mnu=Cat
22. Melin, T., Jefferson, B., Bixio, D., Thoeye, C., De Wilde, W., De Koning, J., Van Der Graaf, J., & Wintgens, T. (2006). Membrane Bioreactor Technology for Wastewater Treatment and Reuse. Desalination: 187, 271-282.
23. Miller, K., Al Hajjiri, M., & Al Hareeri, E. (2011, March). ADWEC Winter 2010 / 2011Demand Forecast(2011 – 2030). Presented at the Abu Dhabi Water and Electricity Company (ADWEC), Beach Rotana Hotel, Abu Dhabi , UAE. Retrieved from http://www.adwec.ae/Documents/PPT/MEED%20%20March%202011%20-%20110.pdf
24. Monnet, F. (2003). An Introduction to Anaerobic Digeation of Organic Wastes - Final Report. Remade Scotland. Retrieved from http://www.biogasmax.co.uk/media/introanaerobicdigestion__073323000_1011_24042007.pdf
25. Muga, H. E., & Mihelcic, J. R. (2008). Sustainability of wastewater treatment technologies. *Journal of Environmental Management*, *88*(3), 437-447. doi:10.1016/j.jenvman.2007.03.008
26. Ortiz, M., Raluy, R. G., & Serra, L. (2007). Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town. *Desalination*, *204*(1-3), 121-131. doi:10.1016/j.desal.2006.04.026
27. Pacific Gas and Electric Company. (2006). Municipal Water Treatment PlantEnergy Baseline Study. San Francisco, CA: SBW Consulting, Inc. Retrieved from http://www.pge.com/includes/docs/pdfs/mybusiness/energysavingsrebates/incentivesbyindustry/wastewater/watertreatmentbaselinestudyreport.pdf
28. Pirani, S. I., Natarajan, L., & Abbas, Z. (2011). Life Cycle Assessment of Membrane Bioreactor Versus CAS Waste Water Treatment: Masdar City and Beyond. Abu Dhabi: Masdar Institute of Science and Technology- WEN502: Industrial Ecology course project report.
29. Radjenović, J., Matošić, M., Mijatović, I., Petrović, M., & Barceló, D. (2007). Membrane Bioreactor (MBR) as an Advanced Wastewater Treatment Technology. In D. Barceló & M. Petrovic (Eds.), Emerging Contaminants from Industrial and Municipal Waste (Vol. 5S/2, pp. 37-101). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/698_5_093
30. Reinhardt, G. (2009, August 11). Energy Opportunities In Wastewater And Biosolids. Water Online. Retrieved from http://www.arizonaenergy.org/News_09/News_Aug09/Energy%20Opportunities%20In%20Wastewater%20And%20Biosolids.htm
31. Renewable Energy World. (2009, January 19). Abu Dhabi Sets 7 Percent Renewables Target | Renewable Energy News Article. Retrieved December 16, 2011, from http://www.renewableenergyworld.com/rea/news/article/2009/01/abu-dhabi-sets-7-percent-renewables-target-54536
32. RSB. (2010). Water and Electricity: Sector Overview 2010-2013. Regulation and Supervision Bureau. Retrieved from http://www.rsb.gov.ae/uploads/Overview20102013.pdf
33. RSB. (2011). About the sector. *Regulation and Supervision Bureau*. Retrieved December 15, 2011, from http://www.rsb.gov.ae/En/PrimaryMenu/index.aspx?SubCatMenu_ID=145&CatMenu_ID=65&PriMenu_ID=177
34. Selke, S. E. (2000). Plastics recycling and biodegradable plastics.
35. Stephenson, T. (2006). Membrane Bioreactors for Wastewater Treatment. http://books.google.ae/books?id=bd_IKSyM80oC&pg=PA7&lpg=PA7&dq=membrane+waste+water+treatment+advantages+and+disadvantages+stephenson&source=bl&ots=-o7K6sXmQ_&sig=qm_UCNPlLk3yY6NsbVLvd9cb7L0&hl=en&sa=X&ei=EjXrTvzxH8Sx8QPntJz2CQ&ved=0CFoQ6AEwAQ#v=onepage&q=membrane%20waste%20water%20treatment%20advantages%20and%20disadvantages%20stephenson&f=false
36. Stillwell, A. S., Hoppock, D. C., & Webber, M. E. (2010). Energy Recovery from Wastewater Treatment Plants in the United States: A Case Study of the Energy-Water Nexus. Sustainability, 2(4), 945-962. doi:10.3390/su2040945
37. Sutton, P. (2006). Membrane Bioreactors for Industrial Wastewater Treatment: Applicability and Selection of Optimal System Configuration. WEFTEC.
38. The National. (2010, November 18). Al Ain recycler leads by local example - The National. Retrieved December 16, 2011, from http://www.thenational.ae/news/uae-news/environment/al-ain-recycler-leads-by-local-example
39. United States Environmental Protection Agency. (2011, December 13). Energy Efficient Wastewater Technology | Region 9: Sustainable Water Infrastructure | US EPA. Retrieved December 11, 2011, from http://www.epa.gov/region9/waterinfrastructure/technology.html
40. Wagner, J., & Eng, B. S. C. (2001). Membrane filtration handbook: Practical tips and hints (Vol. 129). Osmonics.
41. Water Environment Research Foundation. (2008). Wastewater Sludge:A New Resource for AlternativeEnergy and Resource Recovery - Fact Sheet. Retrieved from http://www.werf.org/AM/Template.cfm?Section=Home&TEMPLATE=/CM/ContentDisplay.cfm&CONTENTID=9898
42. World Nuclear Association. (2011, March). Nuclear Power United Arab Emirates | UAE Nuclear Energy | Abu Dhabi | Dubai. Retrieved December 16, 2011, from http://www.world-nuclear.org/info/UAE_nuclear_power_inf123.html