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Sustainability analysis of different SWRO pre-treatment alternatives

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ABSTRACT

The two main alternatives for the pre-treatment of seawater for reverse osmosis desalination, membrane- (UF) and granular media filter based, have been compared and analyzed for their sustainability potential. An environmental life cycle assessment (LCA) has been conducted using commercial software and an economic life cycle costing assessment (LCC) followed according to SETAC guidelines in order to form an eco-efficiency analysis. In addition, other sustainability relevant aspects such as societal factors and process performance have been discussed. The results show why a broad sustainability analysis should be an indispensable part of every process synthesis and how the design and operation of a SWRO desalination plant could be influenced by it.

Keywords: Sustainable development; Pre-treatment; LCA; LCC; Eco-efficiency; LCSA

1. Introduction

Today, product and process sustainability are key issues considered in planning and designing industrial projects. This is especially true when concerning indispensable, broad-spectrum commodities such as water. The process of sea water reverse osmosis (SWRO) desalination is rapidly increasing in popularity to become the most commonly used method of producing potable water in arid, coastal areas. Producing sufficient amounts of desalinated water in a sustainable manner is one of humanity's most immediate challenges.

1.1. Sustainability

The economical development caused by the industrial revolution has induced numerous improvements in the quality of life of many people around the world. However, depletion of resources coupled with heavy environmental emissions have both caused serious and at times irreversible ecological problems, such as increased toxic levels in the air, water and soil, reduced biodiversity, and climate change. At the same time, big technological leaps and rapid economical development have been the assisting background for violent conflicts, uneven wealth distribution and social injustice.

It is clear today that if human beings are to survive on this planet, the continued development of society must be done in a way which will meet the needs of the present, without compromising the prospects of future generations. This is also the definition used by the United Nations' Agenda 21 program for sustainable development [1]. It is mostly depicted using the 'three pillar' model, achieving the goal of sustainability when the three pillars: society, economy and environment complement one another (Fig. 1).

The common approach used today sets out to inspect and analyse each of the three pillars using life cycle methods. The product is examined over its entire

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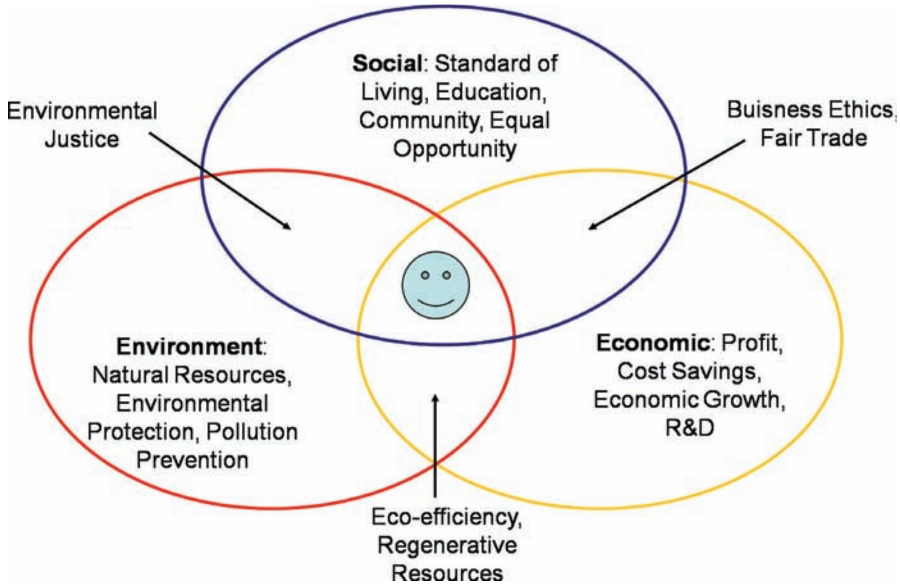

Fig. 1. The three pillars of sustainability: Partial effects are achieved when combining any two of the three aspects.

life cycle, from the excavation of the natural resources, to the production processes, the use-phase by the client, and eventually to the product's disposal/recycling. This so called 'cradle-to-grave' approach is crucial in making sure all aspects are accounted for.

The environmental life cycle assessment is done using the LCA (stands for 'life cycle assessment') method and is the only one of the three that is internationally standardized (ISO 14040 + 14044 [2]). It is composed of four steps: Goal definition, Inventory analysis, Impact assessment, and Interpretation. All calculations and measurements are scaled according to the 'functional unit', a pre-defined quantity which characterizes the process/product and makes it possible to compare alternatives. Two main drawbacks of the LCA in its current form are its inability to consistently integrate elements of risk assessment and to directly quantify the loss of local biodiversity[1].

The economical life cycle assessment is done using the well known life cycle costing method (LCC). Here, all costs attributed to the life cycle of the product are taken into account. It is sometimes referred to as Environmental LCC [3], as it often has a more holistic nature than a normal cost assessment, accounting for all environment related costs (such as recycling) and standing side by side to an environmental LCA. It should be emphasised that LCC should always include only real monetary flows and that overlapping with LCA should be avoided in order not to double count for the same impacts. The aggregated and discounted results of the life cycle costing are usually expressed in the price of the functional unit. There is still no standard for conducting an environmental LCC; however, the guidelines of the Society of Environmental Toxicology and Chemistry (SETAC) are widely accepted by both scholars and industries [3].

The societal life cycle assessment, SLCA, is the most challenging of the three. Although many papers have been published about it in recent years, the huge diversity of hard-to-measure social and societal aspects make this third pillar difficult to quantify and analysed in an objective manner. While some indicators such as plant safety and child labour are easier to estimate, other important indicators such as the extent of workers' freedom of association, their job satisfaction, or the respect for human rights are often not only non-measurable but also cultural dependent and therefore highly subjective. The current state of the art of SLCA [4] is still far from being ripe for international standardisation and will therefore be only introduced here on a qualitative discussion level.

The quantitative level of the sustainability assessment in this work will be limited to the environmental and economical aspects. This might also be referred to as the eco-efficiency analysis (see Fig. 1) as it inspects the trade-offs between better environmental performance and the necessary costs involved or vice versa. Such analyses have been

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[1] Biodiversity issues could be relevant for SWRO on the count of marine life removal through the intake system and the negative effect of the concentrate's high salinity on some marine species.

documented for several other processes and products [5,6]. It should be made clear that all kinds of life cycle assessments are not methods one should use for absolute scaling. They rather serve as tools for comparing alternatives, thus assisting in the process of decision making [7].

Although some have already assessed seawater desalination and its pre-treatment methods according to environmental [8,9] or economical aspects [10], an intergraded, simultaneous discussion approach taking into account all aspects of sustainable development is still missing.

1.2. Seawater reverse osmosis pre-treatment systems

One of the primary parts of SWRO that affects the design, operation, economical and environmental function of the entire process is the pre-treatment. Due to the very delicate nature of the reverse osmosis membranes, it is crucial that the water fed to them would have a good quality. Usually, RO membranes manufacturers are guiding their clients to make sure the feed water has a maximal turbidity level of 1 [NTU] and a silt density index (SDI) of less than 5 (though field operation suggest a maximal SDI of 3 [11]). In addition, further measures against bio-fouling and scaling should often be taken. Since seawater taken from an open source rarely has the sought-after quality, an extensive pre-treatment process is often needed. At the moment, the most common pre-treatment methods include coagulation/flocculation, media filtration and cartridge filtration, as well as the addition of different chemicals to the sea water (for pH control, disinfection, anti-scaling etc.). However, some newer pre-treatment methods have been suggested and examined in recent years, such as the use of membranes (usually UF) or using beach-wells for the water intake. The biggest advantage of the novel methods is their ability to provide feed water to the RO membrane of constant high quality which improves fouling related performance (membrane replacement, cleaning, plant availability etc.). The exact selection and design of the pre-treatment process train is site specific and depends first of all on the water quality parameters (TDS and exact composition, temperature, pH, NTU, SDI, TOC, etc.) which should be measured and monitored in several potential intake locations over the course of one year to account for seasonal and tidal changes. However, other issues (mostly economical) were also shown to be deciding factors [12]. It is the goal of this work to show that environmental and societal issues must also play a major role in the selection and the design of the pre-treatment method.

2. System outline and assumptions

Since the input parameters of the SWRO system as well as its surroundings are location-dependent, a narrowing down of the basic assumptions is needed if one wants to quantitatively assess the sustainability potential of different process designs. The first step that had to be taken was deciding on the input water quality and some basic conditions. It was assumed that a 189 mega litres per day (MLD, or 50 MGD) SWRO plant was to be built on a coast with access to low to moderately fouled surface seawater. The two main alternatives being compared in this study are therefore the conventional pre-treatment method, based on a multi media gravity filter and the membrane pre-treatment method, based on an Ultra Filtration capillary membrane operating in dead-end mode (Fig. 2). The work was based on data acquired from the literature as well as from and personal communication with experts and since the beach-well intake alternative is considered to be imprudent at such production capacities (due to both economical and hydrogeological limitations [12]), it was not possible, at this stage, to fully asses this alternative on the same accuracy level as the media and membrane filtration. This may however change in the future as this method could become more appealing due to its consideration to be the most environmental friendly option [8] and due to maturation of some technologies in the field such as a seabed intake [13] or beach galleries [14]. The following assumptions were made regarding the incoming seawater:

- TDS of 35,000 ppm
- Temperature of 25°C
- pH of 7.8–8
- NTU of 2.5
- SDI of 4.

Based on [15], the conventional set-up was based on coagulation followed by single stage multi-media gravity filters (1.5 m anthracite, 0.75 m sand, 0.6 m garnet) and 10 μ cartridge filters. The RO system is of a single-stage single-pass type with seven elements per pressure vessels, using an isobaric energy recovery device. An over-all recovery rate of 45% with RO flux of 12.75 lmh (7.5 gfd) was used for all calculations. The loading rate of the filters was assumed to be 2.45 $m^3/m^2/h$. No anti-scaling additives were assumed necessary under these conditions. Disinfection by chlorination should also be avoided when possible as it is believed to be the cause of increased RO bio-fouling potential due to the break-down of organics in the water. However shock chlorination (and respectively de-chlorination with sodium bisulfite) might be inevitable from time to time and therefore a weekly intermittent chlorination/de-chlorination was taken into account in the analysis.

The UF alternative consists of a 120 micron strainer followed by inside-out capillary pressure driven membranes and 10 micron cartridge filters. The UF design calculations were based on an average filtration flux

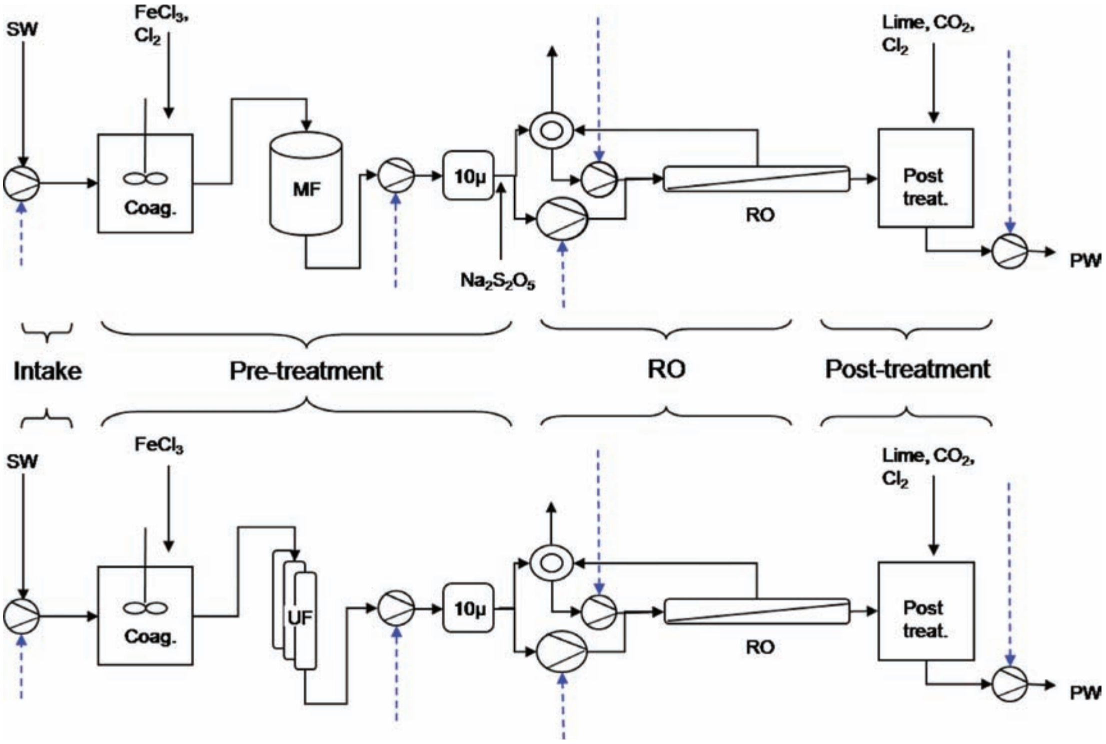

Fig. 2. SWRO with conventional (top) and UF (bottom) pre-treatments.

Table 1
SWRO Operation Data (based on [9,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35]).

Parameter	Filter-based Pre-treatment	UF-based Pre-treatment	Comments
Pre-chlorination (mg/L)	0.8	--	Averaged over the entire operation
Sodium bisulfite (mg/L)	1.84	--	Averaged over entire operation
Chlorine backwash (1/day)	--	1	At 100 ppm
UF chemical soaking (1/year)	--	1	Using citric acid (20000 ppm)
Pre-treatment recovery (%)	94	88	UF backwash every 30 min, media filters once a day
Iron (III) chloride (mg/L)	5	0.5	As Fe, using static mixers
Cartridge filter life time (hour)	1000	2000	
RO membrane life time (year)	5.75	9	Replacement rate reciprocal
RO cleanings per year	6	1	Using citric acid, NaOH and SDBS
Total energy consumption (kWh/m^3)	3,25	3,33	
Plant availability factor (%)	95	97	Susceptibility to intake quality changes

of 85 lmh and a backwash flux of 250 lmh. The same 45% process recovery rate and 12.75 lmh RO flux were considered although a modification to these parameters is possible due to the better filtrate quality of the UF permeate (less fouling potential). This was avoided in order to have a stronger basis of comparison between the alternatives as changing them requires changing of the entire design and operation of the process (for example higher flux means less membrane elements, more pumping power etc.). Pre-chlorination was assumed to be redundant in this case as ultrafiltration provides an efficient barrier against bacteria and viruses and the disinfection of the intake was assumed to happen on a low enough frequency to be ignored of.

Both alternatives use iron (III) chloride as a coagulant agent and incorporate a solids processing system to remove the ferric sludge from the filter/membrane backwash and dispose of it in a landfill. Due to its specificity, complexity and lack of data the operation of this solids processing system was assumed to be similar for both cases and only the sludge release was considered for its environmental effects.

A summary of the important process operation data is given in Table 1.

An important point that should be raised is the fact that in some cases an unanticipated increase of bio-fouling in UF based pre-treatment systems has been documented [11,16,17,20]. This could very well be due to the daily use of chlorine in the UF chemically enhanced backwashes and the fact that some organic molecules can better penetrate through the UF membrane as opposed to the granular filter media. Normally the chlorine is completely washed out of the membranes before the vessel returns to normal filtration mode, but it seems that even this short and partial exposure could be enough for the oxidation of natural organic matter (NOM) and the raised potential of bio-fouling. In that case, an additional disinfection stage, possibly by UV radiation, may be seriously considered, otherwise the theoretically assumed performance enhancement of the RO stage (namely less cleaning in place events) would no longer apply. The addition of a UV unit after the UF membranes has been considered here as a third alternative and is based on information taken from [17]. It should also be mentioned that the general assumption (that is also made here) of improvement in RO life time and cleaning frequency due to membrane pretreatment is at the time speculative and still needs to be proven by long term experience in large plants.

3. Life cycle costing

Now that the systems' outlines and parameters are defined, one can go about with the sustainability assessment. At first, an economical analysis is needed. The method of life cycle costing takes into account all money flows involved in a products' life cycle. As a first step one determines the system's boundaries and the functional unit. In this case we consider the entire 50 MGD SWRO plant as the system and one cubic meter of product water as the functional unit. The use-phase costs will be neglected since the plants' post-treated product water is in a ready to use state for the client without many extra costs involved.[2] The end-of-life (EoL) costs may also be neglected as they are independent of the pre-treatment alternatives and highly depend on the user. On the other hand, input cost-flows would be accounted for using the purchase price and not their "real" cost (excluding suppliers' profit margins) as recommended by SETAC. This is due to the fact that many of the input cost flows relate to commodities that hold very low profit margins and that other costs are hard to estimate as they relate to classified information, such as the production costs of membrane elements. The following assumptions have been made for the purpose of cost estimation:

- Project lie time of 25 years and 6% interest rate
- Land renting costs of 100,000 $ per month (75% of that in the UF case)
- Single RO element cost of 600 $ and installed pressure vessel cost of 8000$.
- Electricity cost of 0.08 $ per kWh
- Chemical costs and ENRI index apply for January 2009.
- Other costs were estimated with the help of [19,36,37].

The breakdown of some of the dominant capital and operation costs is given in Table 2. The results of the overall LCC can be seen in Fig. 3. An interesting conclusion of this analysis is that the membrane pre-treatment system, usually considered more expensive to purchase (requires about 5 million dollars more in capital investment), is actually irrelevant when amortizing the costs over the plants' entire life time, especially when assuming a slightly higher yearly availability factor in the UF case due to the ability of the membranes to better handle sudden changes in intake water quality. The savings resulting from lower chemical consumption (mostly coagulant) and the increased life-time of the RO membranes and cartridge filters are more than enough to cover for the extra costs associated with the UF system operation (such as energy and membrane replacements). Over-all the UF system offers a saving of 3 US Cents per cubic meter of product water: A significant saving of about 2 million Dollars per year for the plant.

All of this changes of course when the possibility of increased bio-fouling in the UF-based plant comes into the picture. In that case, the previous assumptions regarding increased plant availability, lower RO replacement rate and chemical consumption may no longer hold true. In the extreme case where a UV unit might be needed, the additional costs would exceed to a whopping extra 11 Cents per cubic meter: About 8 Cents more than

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[2] This does not hold in case the water needs to be pumped over a long distance or to a great height.

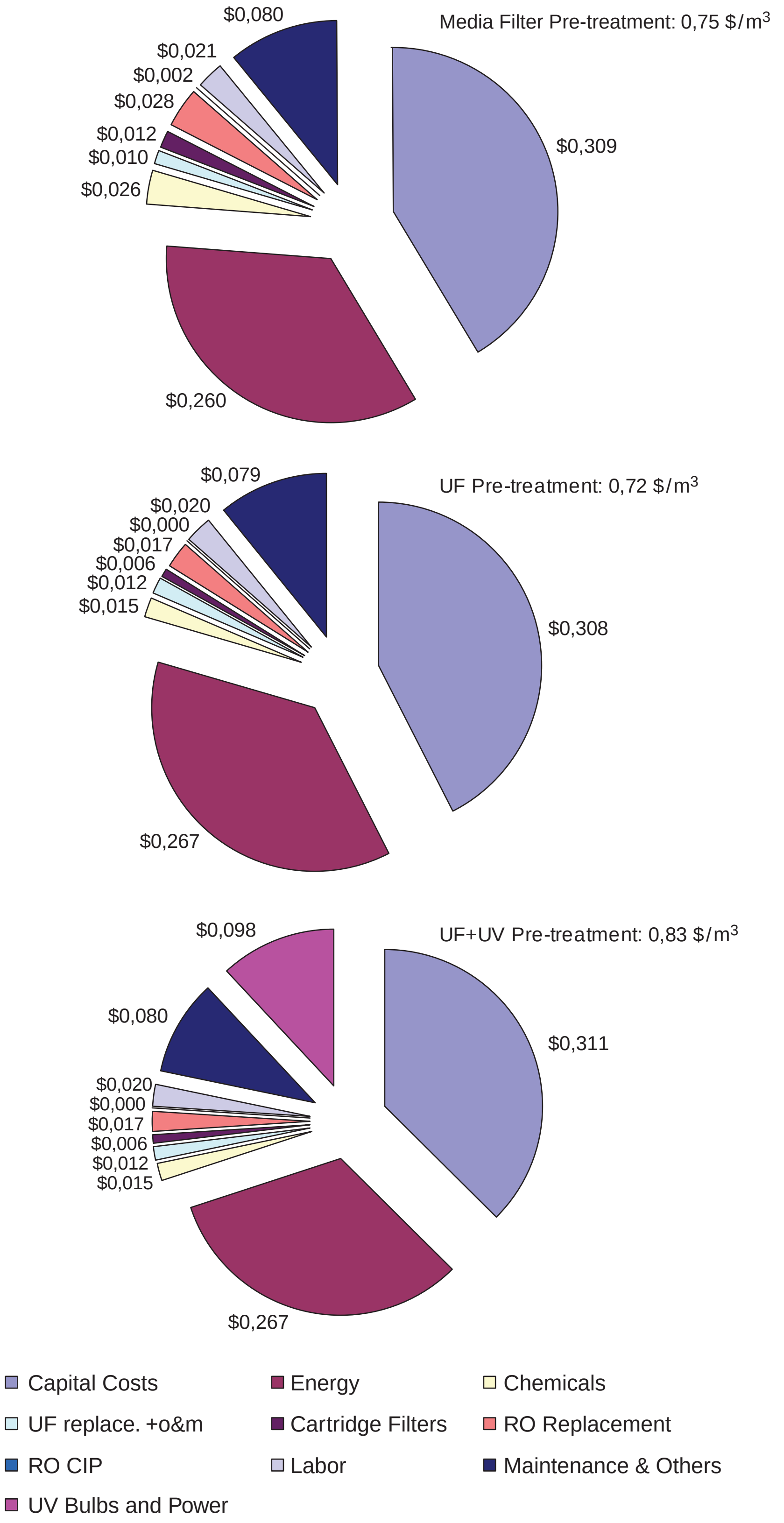

Fig. 3. LCC of the pre-treatment options: MMF (top), UF (middle) and UF+UV (bottom).

Table 2
Major capital cost and operation cost factors in the SWRO.

		UF	Media Filter
CAPEX ($)	Installed Pretreatment Equipment (Vessels/racks, Strainers, Pumps, Piping etc)	25,160,000	24,520,000
	UF Membranes/Granular Media	10,080,000	1,127,000
	Coagulation System	531,000	5,400,000
OPEX ($/year)	NaOCl in Pretreatment	23,000 (CEB)	312,000
	FeCl3	28,000	273,000
	Na2SO5	-	177,000
	UF/Media Replacement and Maintenance	1,740,000	596,000
	RO Replacement	1,170,000	1,830,000
	Cartridge Filters	416,000	816,000

the conventional method. The main reason lies in the bigger demand of electricity needed to produce the ultra violet radiation: A cubic meter of product water would require a total of 4.52 kWh in that case (as opposed to the estimated 3.33 kWh without the UV unit). In conclusion, the UF pre-treatment has an economical advantage as long as increased bio-fouling does not occur.

4. Environmental life cycle assessment

Now that the economical results were introduced, the next pillar of sustainability, environment, has to be addressed. The method used, LCA, is in agreement with the ISO 14040 + 14044 standards and was carried out using the GaBi 4® software [38]. The process plans can be seen in Fig. 4. The choice of this particular commercial tool was based on its wide acceptance by the industry.

4.1. Definition of scope and goals

The goal was set out to determine the environmental influences of the SWRO plant when confronted with the issue of alternating pre-treatment methods. Both options of UF and UF+UV for the membrane pre-treatment were examined. Unfortunately, due to lack of documented information, the impacts of production and transportation of the technical equipment (including membrane and UV lamp replacement) could not be taken into account. It was however suggested in the past that these impacts are minor when compared to those resulting from the plant operation [9,18]. The system's boundaries were set to be the same as the plant's boundaries and the functional unit was defined as one cubic meter of product water.

4.2. Life cycle inventory (LCI)

All chemical and energy streams were averaged over the operation time and scaled according to the functional unit. The information for the upstream chains was based on information from the software's internal data-base, the German ProBas project [39] and previous publications in this area [18]. As a first approximation, the electricity grid supply was assumed to have a typical European fuel-mix of about 50% coal, 10% gas, 25% nuclear and 15% renewables.

4.3. Life cycle impact assessment

At this point LCI results were attributed to their environmental influences and impacts. Three of these impacts are shown in Fig. 5. Since it is not mandatory by the ISO standards, the aggregation of the impacts into a single environmental score was avoided for two reasons: (1) An aggregation requires the use of arbitrary normalization and weighting factors that may subjectively alter the results. (2) A single dimensionless score is harder to comprehend as opposed to more realistic quantities such as equivalent kgs of CO2 emissions.

4.4. Interpretation

The results of the impact assessment showed a clear dominance of the energy production over the impacts resulting from the other processes. As it can be seen in Fig. 5, the green house gas emissions of the UF alternative are about 70 g higher (in eq. CO2 per m^3 product water) than those resulting from the conventional media filtration. This alludes to a yearly additional emission of about 4600 ton CO2 (equivalent to the average yearly emission of about 3300 cars). Not a very large amount, but it definitely disagrees with the desired global goal of massive CO2 reduction in the near future. This is even more relevant when considering the fact that SWRO desalination is often implemented in countries that traditionally use a fuel mix based on a much higher content

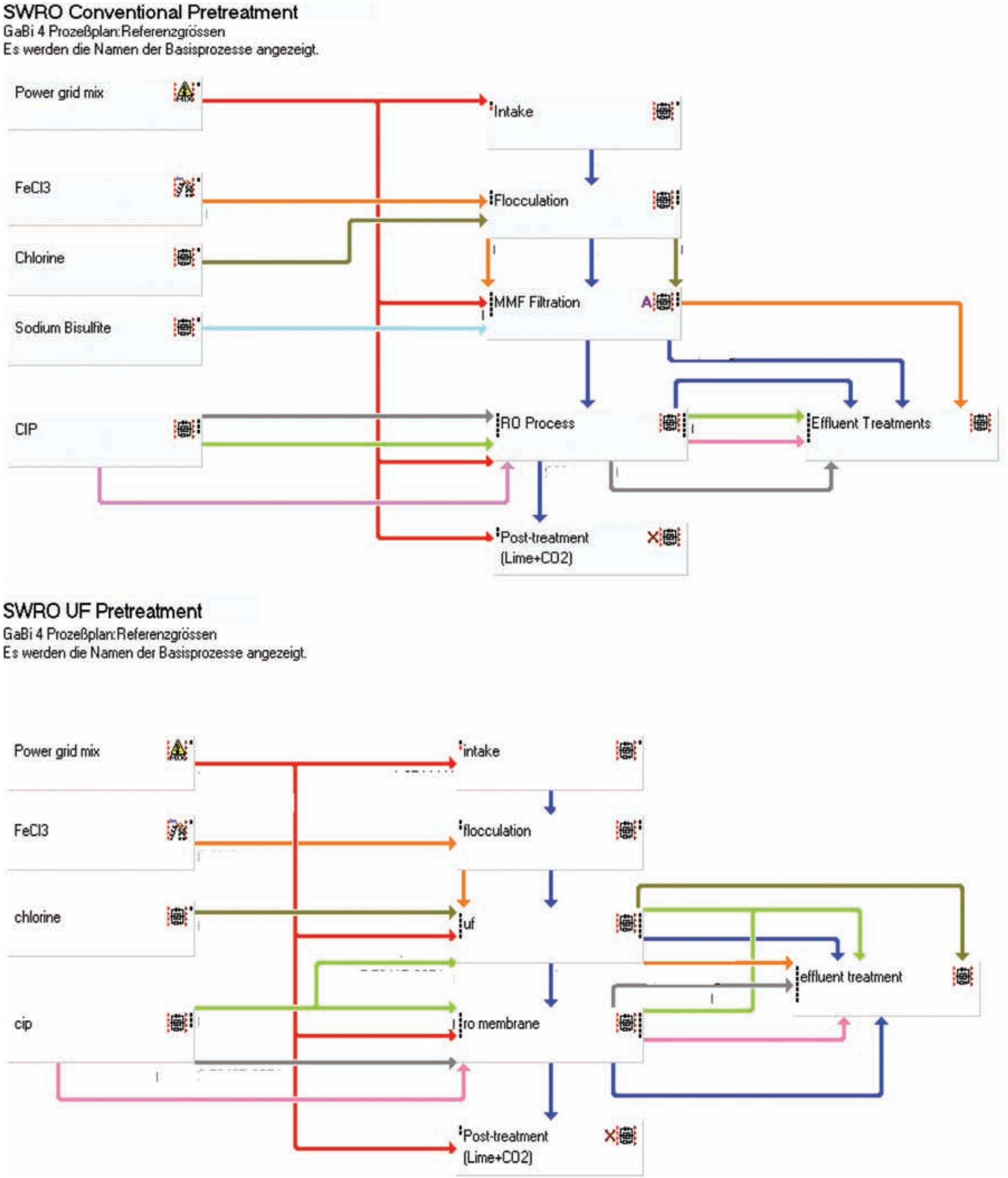

Fig. 4. Gabi4 process plans: Conventional (top)- and membrane –pretreatment (bottom).

of fossils (MENA region). The implementation of a UV system significantly raises the CO2 emissions further by additional 860 grams per cubic meter. Furthermore, as the de-chlorination of the UF backwash water is not as obvious as it is in the conventional process (where it must be done in order to protect the RO membranes), the resulting marine eco-toxicity effects could be significant when the water is discharged into the sea without sufficient treatment (as in the case shown in the middle diagram in Fig. 5).

Two cases in which the UF treatment showed better environmental performance characteristics than its media filtration parallel were: (1) Ozone layer depletion: the reduced amount of needed coagulant means

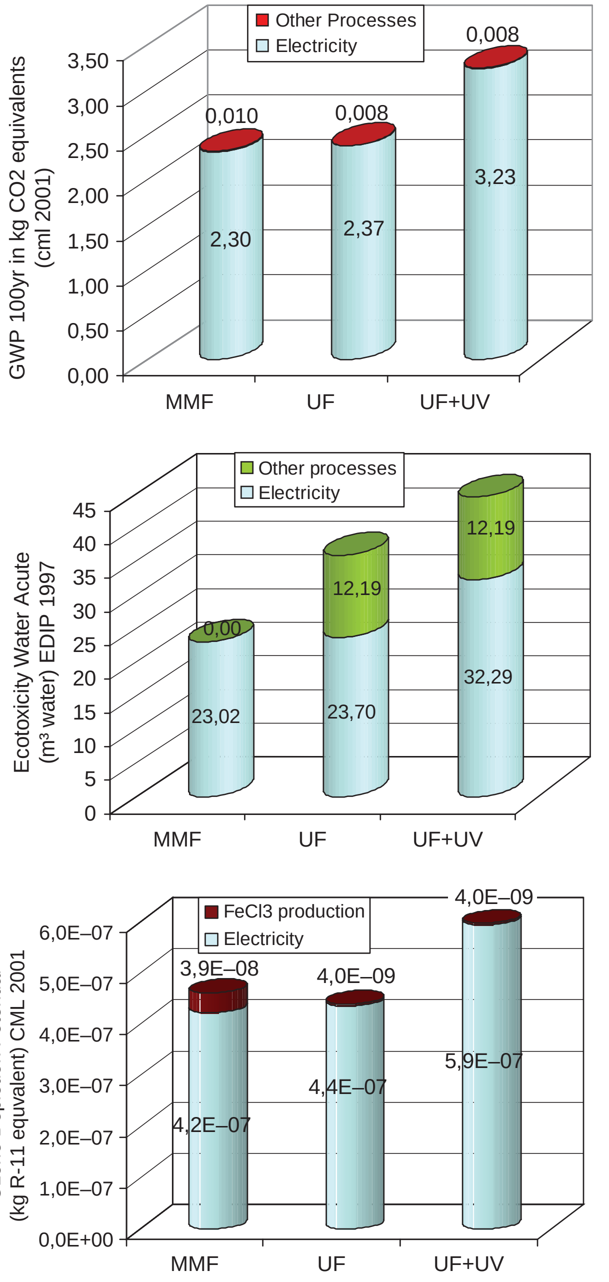

Fig. 5. Three of the environmental impacts caused by the SWRO process: Global warming potential (top), marine ecotoxicity (middle) and ozone depletion potential (bottom).

fewer emissions of chlorofluorocarbons in its production process. This impact is however quite small due to the minor amounts being emitted. (2) Land-use: membrane pre-treatment has a 30–50% smaller foot print [19] but this effect was already taken into consideration in the LCC and therefore is not shown here.

The iron sludge disposal proved to have negligible environmental impacts in both cases due to the iron's very low ecotoxicity.

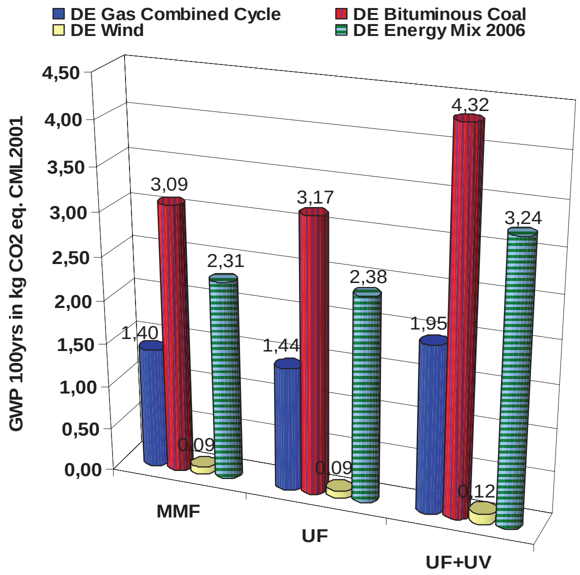

Fig. 6. SWRO Global Warming Potential in equivalent kgs of CO2 for different energy sources and pretreatment options.

5. Eco-efficiency and sustainability potential

The next step after assessing the economic and environmental impacts is their fusion into one measurable aspect, the eco-efficiency, while at the same time considering the qualitative/social aspects of the alternatives. Eco-efficiency is usually defined as the relation between environmental improvements to economical expenditure. At this point an aggregation of the environmental impacts to a single environmental performance score is usually unavoidable. The method of CML 2001 experts IKP [38] was used to produce the single, weighted, overall environmental impact scores shown in Table 3.

It is obvious that the UF + UV alternative is the less preferable of the three as it means more costs for less environmental performance. As to the sustainability based decision between a conventional and a UF pre-treatment, it is clear that one should proceed with caution. If the main goal is to reduce the total environmental impacts, then the conventional pre-treatment at the current state of the art still has an advantage over the membrane pre-treatment. However the relative difference in environmental performance (about 2.4%) is smaller than the difference in LCC values, (4%)

Table 3
Eco-Efficiency assessment of the Pre-treatment alternatives.

	LCC ($)	CML 2001 IKP (x 10^{-13})
Conventional	0.75	6.28
UF	0.72	6.43
UF + UV	0.83	8.76

Table 4
Societal and performance aspects of the pre-treatment alternatives.

	Media Filter	UF	Comments
Human Labor Intensity	👍	👍👍	UF: More automation, less RO cleaning.
Noise Levels	👍👍	👍	UF: More pumping power.
Safety	👍	👍	UF: Smaller chemical demand but more moving parts and pumping power.
Equal Opportunity / Design Flexibility	👍👍	👍	UF: Proprietary patented systems bonding the plant to a single manufacturer. Media Filter: media is interchangeable and tanks could be converted to hold membranes.
Robustness	👍	?	UF: Risk of increased RO bio-fouling should be further investigated.

which gives an advantage to the membrane, especially in case the environmental impacts resulting from electricity production could be reduced. Such a reduction could be achieved by changing the electricity supply to a "greener" one such as a gas combined cycle (as in the Ashkelon plant [40]) or wind turbines (as in Sydney and Perth [41]). The effects of such on the global warming potential of the entire process can be seen in Fig. 6. Another promising option would be to optimize the design and operation of the membrane trains with the goal of minimizing the energy and chemical consumption, for example by working with lower filtration fluxes [21,22]. However a trade off with increased capital costs must be considered (lower flux means more membrane area is needed).

Qualitative societal and operation performance issues might also be helpful in making a design decision. The UF employs a higher degree of automation which on one hand reduces the required human intervention but on the other hand includes many small moving technical parts which are more susceptible to malfunctions. Membrane pre-treatment systems are also limited in their flexibility as they are currently all proprietary systems, exclusively bonded to one installing manufacturer's membranes and services (unlike the RO system). Additionally, despite being more robust against sudden changes in intake water conditions (already taken into account in the plant availability factor), the membrane systems could be problematic in the case of increased bio-fouling. Even in sporadic events this would mean higher chemical and energy consumption as well as higher replacement rates of the RO membranes and cartridge filters, negatively affecting the eco-efficiency of the plant. In more persistent cases, the addition of a sterilization process (such as UV irradiation) might be inevitable. These and other qualitative aspects are addressed in Table 4. The membrane stands at a slight disadvantage, mostly due to the issues of flexibility and robustness.

6. Conclusion

The goal of this work was to objectively assess the current sustainability of the most common SWRO pre-treatment methods. This analysis showed that when integrating all three aspects of sustainability, the membrane pre-treatment in this case, although being more economical, is somewhat less preferable regarding the environmental and societal aspects, mostly due to its higher energy demand (which shows a strict dominance over the chemical use) and to its lower degree of flexibility (proprietary systems) and robustness (bio-fouling risk). Therefore when working with non difficult waters (as was the case assessed here), the gravity media filter is currently still a more sustainable technological solution. In other cases, the needed extension of the conventional pre-treatment process train (to include flocculators, settlers, DAF, second stage filtration, etc.) will decrease its eco-efficiency, thus favouring with the membrane pre-treatment. The membrane based pre-treatment is never the less a promising technology still at the beginning of its learning curve, with a large improvement potential at its disposal. Further optimization of its design and operation concerning the over-all process sustainability is called for.

Acknowledgments

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References

[1] UNCED Earth Summit of 1992, Agenda 21: Earth Summit - The United Nations Program of Action from Rio, United Nations Publications 1993.

[2] International Organization for Standardization, Geneva, Switzerland, ISO 14040:2006 + 14044:2006, Environmental manage-

ment – Life cycle assessment – Principles and framework + Requirements and guidelines, http://www.iso.org.

[3] D. Hunkeler, K. Lichtenvort, G. Rebitzer et al., Environmental Life Cycle Costing, Society of Environmental Toxicology and Chemistry (SETAC), Florida 2008.

[4] UNEP/SETAC Life Cycle Initiative (edited by C. Benoît and B. Mazijn), Guidelines for Social Life Cycle Assessment of Products, United Nations Environment Programme, 2009.

[5] R. Grießhammer, M. Buchert, C. Gensch, C. Hochfeld, A. Manhart, I. Rüdenauer, PROSA – Product Sustainability Assessment (Final Report), Institute for Applied Ecology, Freiburg 2007.

[6] P. Saling, A. Kicherer, Die Ökoeffizienz-Analyse nach BASF, Mitteilungen der Fachgruppe Umweltchemie und Ökotoxikologie 10.Jahrg. 2004/ Nr.1.

[7] W. Kloepffer, Life Cycle Sustainability Assessment of Products, Int J LCA, 13 (2) p. 89–95, 2008.

[8] S. Latteman, Environmental Impact assessment of Desalination Plants, Lecture Notes, DME Seminar on Environmental Issues in Desalination, Berlin 2009.

[9] C. Fritzmann, C. Niewersch, A. Jansen, T. Wintgens, T. Melin, Comparative Life Cycle Assessment Study of Pretreatment Alternatives for RO Desalination, IDA World Congress-Maspalomas, Gran Canaria –Spain October 21–26, 2007.

[10] P. Glueckstern and M. Priel, Comparative Cost of UF vs. Conventional Pretreatment for SWRO Systems, Desalination & Water Reuse, 12(4) and 31(1) (2003) 34–39.

[11] M. Wilf, RO, NF, Membrane filtration and MBR Technology for Potable and Wastewater Reclamation Applications, Lecture Notes, EDS Course, L'Aquila 2009.

[12] Unesco IHE and the Ben Gurion University, A comprehensive critical evaluation on conventional, membrane–based and novel pre-treatment procedures for SW and BW desalination, MEDINA Project Progress Report (online), 2007.

[13] T. Peters, D. Pintó, E. Pintó, Improved seawater intake and pretreatment system based on Neodren technology, Desalination, 203 (2007) 134–140.

[14] R. G. Maliva, T. M.Missimer, Self-cleaning beach gallery design for seawater desalination plants, EDS Desalination for the Environment, Clean Water and Energy, Baden-Baden, Germany 2009.

[15] Li, N. et al., Advanced Membrane Technology and Applications, Wiley, 2008, p. 47–86.

[16] Reiss, C.R. et al, Pretreatment and Design Considerations for Large-Scale Seawater Facilities, Desalination and Water Purification Research and Development Program Report No. 137, U.S. Department of the Interior: Bureau of Reclamation, Denver 2008.

[17] Reiss, C.R. et al, Evaluation of Desalination on Waters Under the Influence of Surface Water Runoff for Pretreatment, Water Quality, and Pathogen Removal Performance, Desalination and Water Purification Research and Development Program Report No. 113, U.S. Department of the Interior: Bureau of Reclamation, Denver 2007.

[18] Vince, F., Design Approach for the Improvement of the Economic and Environmental Performances of Potable Water Supply, Ecole Polytechnique FLausanne, Dissertation 2008.

[19] Wilf, M. et al., The Guidebook to Membrane Desalination Technology, Balaban 2007.

[20] P.–J. Remize, J.F. Laroche, J. Leparc, J.C. Schrotter, A Pilot-Scale Comparison of Granular Media Filtration and Low-Pressure Membrane Filtration for Seawater Pretreatment, Desalination Water Treat., 5 (2009) 6–11.

[21] J. Xu, G. Ruan, X. Chu, Y. Yao, B. Su, C. Gao, A pilot study of UF pretreatment without any chemicals for SWRO desalination in China, Desalination, 207 (2007) 216–226.

[22] M. Busch, R. Chu, U. Kolbe, Q. Meng, S. Li, Integrated ultrafiltration and reverse osmosis membrane system for seawater desalination – 1000 days field experience with DOW UF and FILMTEC technology in the WangTan DaTang power plant, Euromed 2008, Desalination Cooperation among Mediterranean Countries of Europe and the MENA region, Dead Sea, Jordan, 2008.

[23] M. Busch (DOW Water Solutions), Personal Communication. June 2009.

[24] S. Lattemann, Personal Communication. June 2009.

[25] K. Kinser, P. Shen, S. Harrison, M. Price, Pretreatment Performance for Desalinating Seawater with Fluctuating Water Quality due to Circumstances at Moss Landing, AWWA MTC proceedings, 2009.

[26] L. Henthorne, Evaluation of Membrane Pretreatment for Seawater Reverse Osmosis Desalination, Desalination and Water Purification Research and Development Program Report No. 106, U.S. Department of the Interior: Bureau of Reclamation, Denver 2007.

[27] M. Wilf, C. Bartels, Integrated Membrane Desalination Systems Current Status and Projected Development, Desalination and Water Reuse International Forum & Exhibition, Tianjin, China 2006.

[28] S.C.J.M. van Hoof, J.G. Minnery, and B. Mack, Dead-end ultrafiltration as alternative pre-treatment to reverse osmosis in seawater desalination: A case study. Desalination, 139 (2001) 161–168.

[29] A. Brehant, V. Bonnelye, and M. Perez, Comparison of mf/uf pretreatment with conventional filtration prior to ro membranes for surface seawater desalination, Desalination, 144 (2002) 353–360.

[30] P. Glueckstern, M. Priel, and M. Wilf, Field evaluation of capillary uf technology as a pretreatment for large seawater ro systems, Desalination, 147 (2002) 55–62.

[31] G. Pearce, S. Talo, K. Chida, A. Basha, and A. Gulamhusein, Pretreatment options for large scale swro plants: Case studies of uf trials at kindasa, saudi arabia, and conventional pretreatment in spain, Desalination, 167 (2004) 175–189.

[32] J.D. Zhang, Y.W. Liu, S.M. Gao, C.Z. Li, F. Zhang, H.M. Zen, and C.S. Ye, Pilot testing of outside-in uf pretreatment prior to ro for high turbidity seawater desalination, Desalination, 189 (2006) 269–277.

[33] J.D. Zhang, S. Gao, H. Zeng, F. Zhang, C. Li, Y. Liu, D. Fu, and C. Ye, Pilot testing of two inside-out uf modules prior to ro for high turbidity seawater desalination, Desalination, 196 (2006) 66–75.

[34] H. Ludwig, Energy Consumption of Reverse Osmosis Seawater Desalination—Possibilities for Its Optimisation in Design and Operation of SWRO Plants, EDS desalination for the environment: Clean water and energy, Baden-Baden, Germany 2009.

[35] N. Voutchkov, Pretreatment Technologies for Membrane Seawater Desalination, Australian Water Association, 2008.

[36] I. Moch et al., WT Cost II: Modeling the Capital and Operating Costs of Thermal Desalination Processes Utilizing a Recently Developed Computer Program that Evaluates Membrane Desalting, Electrodialysis, and Ion Exchange Plants, Desalination and Water Purification Research and Development Program Report No. 130, U.S. Department of the Interior: Bureau of Reclamation, Denver 2008.

[37] Affordable Desalination Collaboration (ADC), Dow SW30HR-380 NPV, Online Spreadsheet: http://www.affordabledesal.com, 2006.

[38] PE International and LBP University of Stuttgart, GaBi 4® Instructions for Advanced example, Software Documentation, 2007.

[39] German Institute of Applied Ecology and Ministry of Environment, Prozessorientirte Basisdaten für Umweltmanagement-Instrumente (ProBas), Online databse: www.probas.umweltbundesamt.de, 2008.

[40] G. Kronenberg, The largest SWRO plant in the world—Ashkelon 100 million m3/y BOT project, Desalination, 166 (2004) 457–463.

[41] I. El Saliby, Y. Okour, H.K. Shon, J. Kandasamy, In S. Kim, Desalination plants in Australia, review and facts, Desalination, 249 (2009) 1–14.