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Carbon footprint of seawater reverse osmosis desalination pre-treatment: Initial results from a new computational tool

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ABSTRACT

A carbon footprint represents the overall CO_2 equivalent emissions embodied in a specific product over its entire life cycle. In this work we present an easy to use software tool developed in Excel which allows for the calculation of a carbon footprint to be conducted by non professional. The tool was specifically designed according to life cycle assessment (LCA) standards to be used with water treatment processes but can be modified for other processes as well. Using a case study involving the SWRO pre-treatment process in the Palm Jumeirah plant a calculation of the carbon footprint of 1 m^3 of pre-treated seawater was carried out and the hot spots at which process improvements can be made were identified.

Keywords: Carbon footprint; SWRO; Pre-treatment; Palm Jumeirah

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1. Introduction

Seawater reverse osmosis (SWRO) desalination is rapidly becoming a global common method of producing drinking water in coastal regions suffering from water stress. The pre-treatment process is an important part of SWRO which makes sure the RO membranes can be operated optimally with as little fouling as possible. The design of a pre-treatment process is a gray area which does not follow strict guidelines. It is usually site and plant specific, based on pure local techno-economical considerations. However, environmental and societal considerations are already starting to play a larger role in the pre-treatment process synthesis and they are expected to do even more so in the future [1–3]. Such a consideration could be the influence of the pre-treatment system on the global climate. A high quality, high accuracy assessment of the climate change potential of an existing pre-treatment system as well as the inclusion of such an assessment in the design stage of a new pre-treatment system have not yet been reported in the literature.

2. Materials and methods

In order to account for the global warming potential of a specific process or product, the information regarding the emissions embedded in its system must be carefully collected and assessed. The product carbon footprint

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(PCF) is a way of doing just that. Based on the already well established life cycle assessment (LCA [4]) methodology (ISO 14040:2006) the overall greenhouse gas emissions embodied in specific goods and services during their entire life-time, from excavation of raw materials to manufacturing, supply chains, use-phase and disposal, are added and assessed for their global warming effect.

The public general interest in carbon emissions has resulted in a need for a standard and easy to use assessment system which is defined in layman's terms. This has caused ISO to start developing a specific international standard for the issue (ISO 14067: Carbon Footprint of Products – Quantification and Communication) which is expected to be released in 2011. In Great Britain, Carbon Trust have already published a Publicly Available Specification (PAS 2050 2008) document which serves as a good orientation for non-professionals in this field [5].

Once the product's carbon footprint is calculated one can identify the spots responsible for the greater part of the emissions and act to reduce them. A comparison and choice between processes and products based on their carbon footprint is also made possible. However, a note of caution should be given at this point warning from over emphasizing the carbon foot print. Even though climate change currently stands at the top of the list of the world's environmental agenda, it is only one of the many environmental impacts a product may have during its life cycle. Overlooking other impacts (such as acid rain, resource depletion, human-/eco-toxicity, land use etc.) may lead to a problem shift from one environmental demerit being fixed to another one being created. For example, according to the carbon footprint alone any waste water treatment process would be considered uncalled-for, which is obviously not a desired case in reality. In order to fully judge a product's environmental performance a full LCA should be prepared [6,7].

Performing a carbon footprint calculation according to the LCA methodology would usually require using one of the commercial LCA software available on the market today. This would require not only a costly investment paid for limited user access but also effort in getting oneself familiarized with the functionality of a heavy program which is not carbon footprint specific. Another disadvantage is that such programs are usually patent-protected, closed source and non-manipulated software so they cannot be integrated to work with process design tools, programmable logic controllers (PLC) etc. For these reasons using such a software is often intimidating for small to medium sized companies and clients, hindering the global availability of information regarding product-specific greenhouse gas emissions. A simpler, user friendlier solution which is open to modifications and improvements is therefore needed.

The tool presented here is an easy to use Excel based, VBA (Visual Basic for Applications) customized workbook which is based on the LCA methodology and relies on freely available databases (like GEMIS or ecoinvent [8,9]) and publications. It can be modified by anyone familiar with Visual Basic and is populated with data specifically relevant for SWRO processes (pumps, chemical dosing, membrane filtration etc). It was developed based on the pre-treatment process at the Dubai Palm-Jumeirah SWRO desalination plant using real plant data and information.

The pre-treatment process at Palm-Jumeirah (Fig. 1) involves intermittent chlorination of the open intake water, bar screens and a travelling band screen, followed by the intake (transfer) pump, pH adjustment and inline coagulation. The seawater then goes through a strainer to the Seaguard membranes where it is filtered and collected in a tank. Using water from that tank, periodical backwashes and chemically enhanced backwashes using acid, base and chlorine are taking place. The entire wastewater from the different process units is being collected, neutralized and disposed off. The main information about the design and field operation of this process is available in [10–12].

The following assumptions were made during the analysis:

- A functional unit of 1 m^3 RO feed water.
- A plant life time of 30 years and a membrane life time of 10 years.
- The construction, operation and maintenance of all the process equipment (including the pipeline) were considered but the decommissioning was neglected due to lack of information and assuming it has a comparatively small effect.
- Most chemicals and raw materials were assumed to be transported by sea freight from either China or India. The membrane skids were transported from the Netherlands.
- Transportation of personnel was not considered.
- In case the emissions information for a specific component could not be found in the databases or literature, approximations were made based on similar components.

For the first time in such an analysis the carbon footprint embodied in the production and transportation of the UF membranes was also precisely taken into account. The material and energy streams at the Norit membrane plant in Enschede (NL) involved in the production of a single Seaguard UF membrane module were accounted for their individual global warming potential (Fig. 2). Using the tool described below, the carbon footprint of a single membrane element at the plant was calculated to be 3.01 tons CO_2 eq. per element.

3. Results

As the spreadsheets in the tool were programmed to work according to the LCA methodology the user is

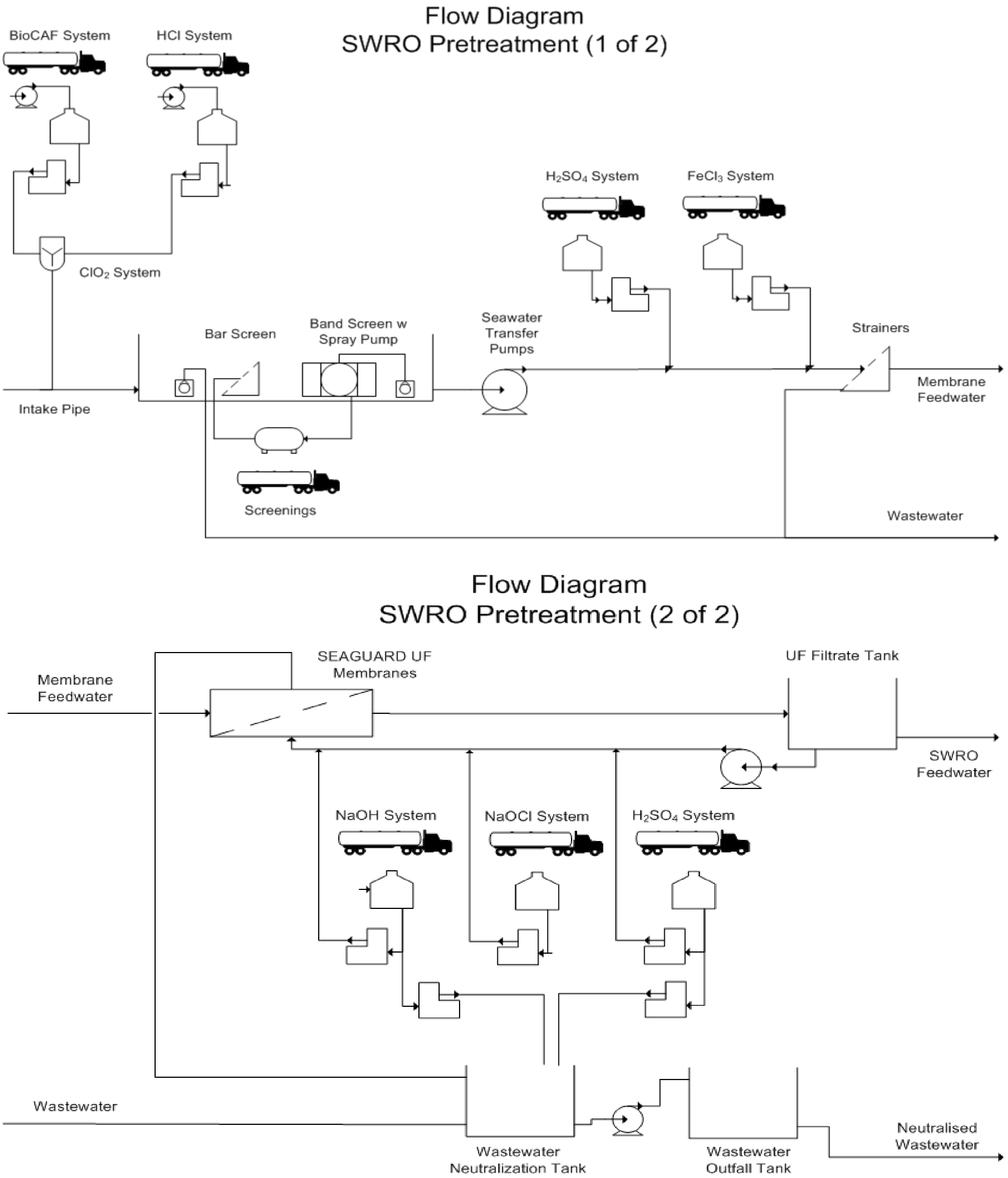


Fig. 1. The Palm-Jumeirah plant pre-treatment process flowsheet considered for the carbon footprint.

asked to successively fill out the information following the common LCA working steps. At the cover page the user gives some basic info about the project, time and place and people involved. In the goal definition page the user defines the objectives, intended application and reasons for doing the assessment (Fig. 3). In the scope

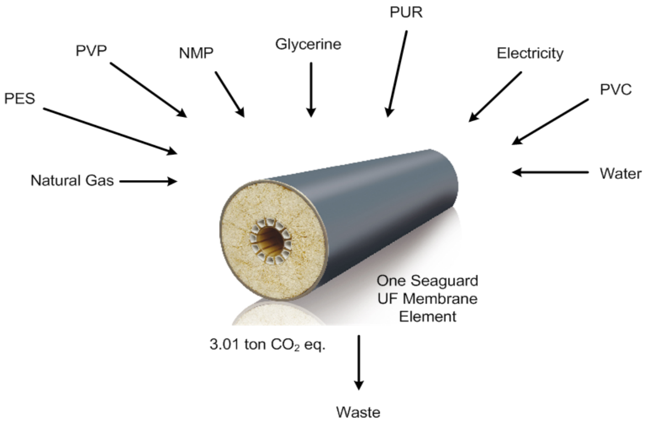
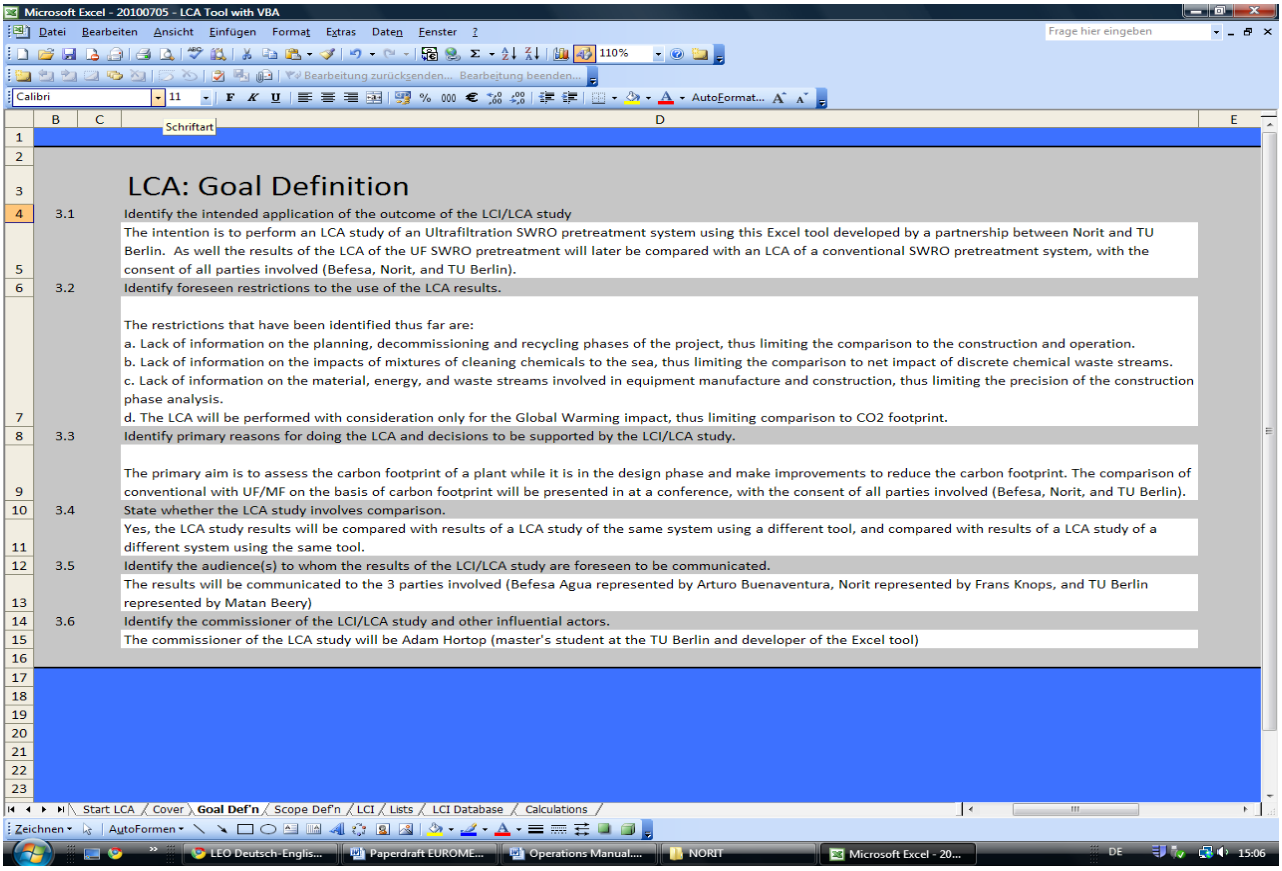


Fig. 2. The material and energy streams involved in the production of a membrane element at the plant.

definition the boundary conditions are being set: The user defines the system (preferably using a flowsheet), the assumptions, the functional unit and the time frame (Fig. 4). The next step is the life cycle inventory in which the actual accounting and calculation takes place. The user defines all the processes involved in the system and their in/output streams divided into construction and operation (Fig. 5). Since a large amount of data needs to be collected this is the most cumbersome step. For example the air compressor system inventory is given in Table 1.

In order to perform a carbon footprint assessment it is necessary to assign values of carbon dioxide equivalent emissions to each resource that is used, consumed or wasted in the life of the product or process. This assignment is only possible by two methods: First, measuring the emissions created during the cradle to gate life of the resource being used (this is extremely difficult for any real process), or second, assuming that the resource used is similar to a resource that has already been measured and listed in a database. This second method is the one used in this tool. In order to assign a measured resource to an actual resource we must first define the measured resource. This is done in the "Best Approximation Resource/Emission" table (Table 2) which is basically the tool's internal database of carbon allocations.

In case a stream cannot be found in the database the user needs to choose an approximation (for example carbon steel instead of duplex) or update the database manually after doing some literature research. Finally the different contributions are being automatically summed up according to the total flows during the plant's entire



LCA: Goal Definition

3.1 Identify the intended application of the outcome of the LCI/LCA study

The intention is to perform an LCA study of an Ultrafiltration SWRO pretreatment system using this Excel tool developed by a partnership between Norit and TU Berlin. As well the results of the LCA of the UF SWRO pretreatment will later be compared with an LCA of a conventional SWRO pretreatment system, with the consent of all parties involved (Befesa, Norit, and TU Berlin).

3.2 Identify foreseen restrictions to the use of the LCA results.

The restrictions that have been identified thus far are:
a. Lack of information on the planning, decommissioning and recycling phases of the project, thus limiting the comparison to the construction and operation.
b. Lack of information on the impacts of mixtures of cleaning chemicals to the sea, thus limiting the comparison to net impact of discrete chemical waste streams.
c. Lack of information on the material, energy, and waste streams involved in equipment manufacture and construction, thus limiting the precision of the construction phase analysis.
d. The LCA will be performed with consideration only for the Global Warming impact, thus limiting comparison to CO2 footprint.

3.3 Identify primary reasons for doing the LCA and decisions to be supported by the LCI/LCA study.

The primary aim is to assess the carbon footprint of a plant while it is in the design phase and make improvements to reduce the carbon footprint. The comparison of conventional with UF/MF on the basis of carbon footprint will be presented in at a conference, with the consent of all parties involved (Befesa, Norit, and TU Berlin).

3.4 State whether the LCA study involves comparison.

Yes, the LCA study results will be compared with results of a LCA study of the same system using a different tool, and compared with results of a LCA study of a different system using the same tool.

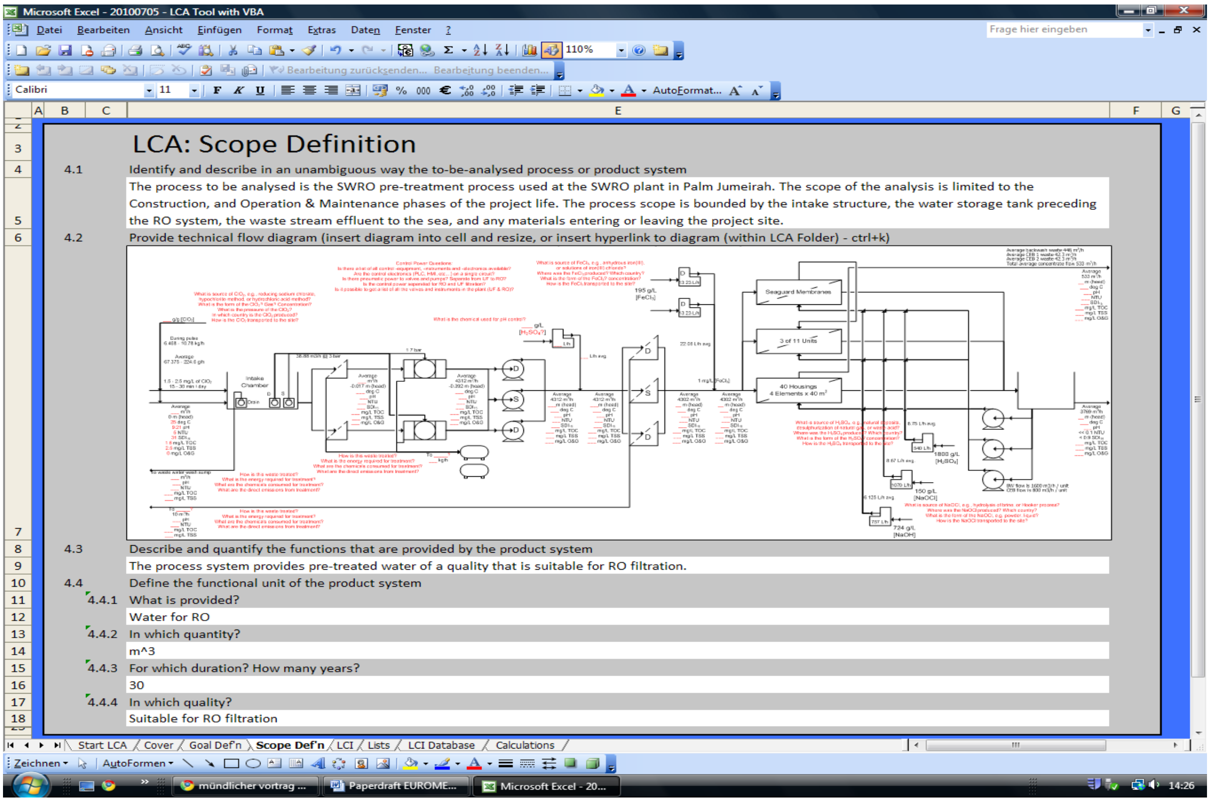
3.5 Identify the audience(s) to whom the results of the LCI/LCA study are foreseen to be communicated.

The results will be communicated to the 3 parties involved (Befesa Agua represented by Arturo Buenaventura, Norit represented by Frans Knops, and TU Berlin represented by Matan Beery)

3.6 Identify the commissioner of the LCI/LCA study and other influential actors.

The commissioner of the LCA study will be Adam Hortop (master's student at the TU Berlin and developer of the Excel tool)

Fig. 3. A screenshot of the Goal Definition worksheet in the CO_2 footprint computational tool.



LCA: Scope Definition

4.1 Identify and describe in an unambiguous way the to-be-analysed process or product system

The process to be analysed is the SWRO pre-treatment process used at the SWRO plant in Palm Jumeirah. The scope of the analysis is limited to the Construction, and Operation & Maintenance phases of the project life. The process scope is bounded by the intake structure, the water storage tank preceding the RO system, the waste stream effluent to the sea, and any materials entering or leaving the project site.

4.2 Provide technical flow diagram (insert diagram into cell and resize, or insert hyperlink to diagram (within LCA Folder) - ctrl+k)

4.3 Describe and quantify the functions that are provided by the product system

The process system provides pre-treated water of a quality that is suitable for RO filtration.

4.4 Define the functional unit of the product system

4.4.1 What is provided?

Water for RO

4.4.2 In which quantity?

m^3

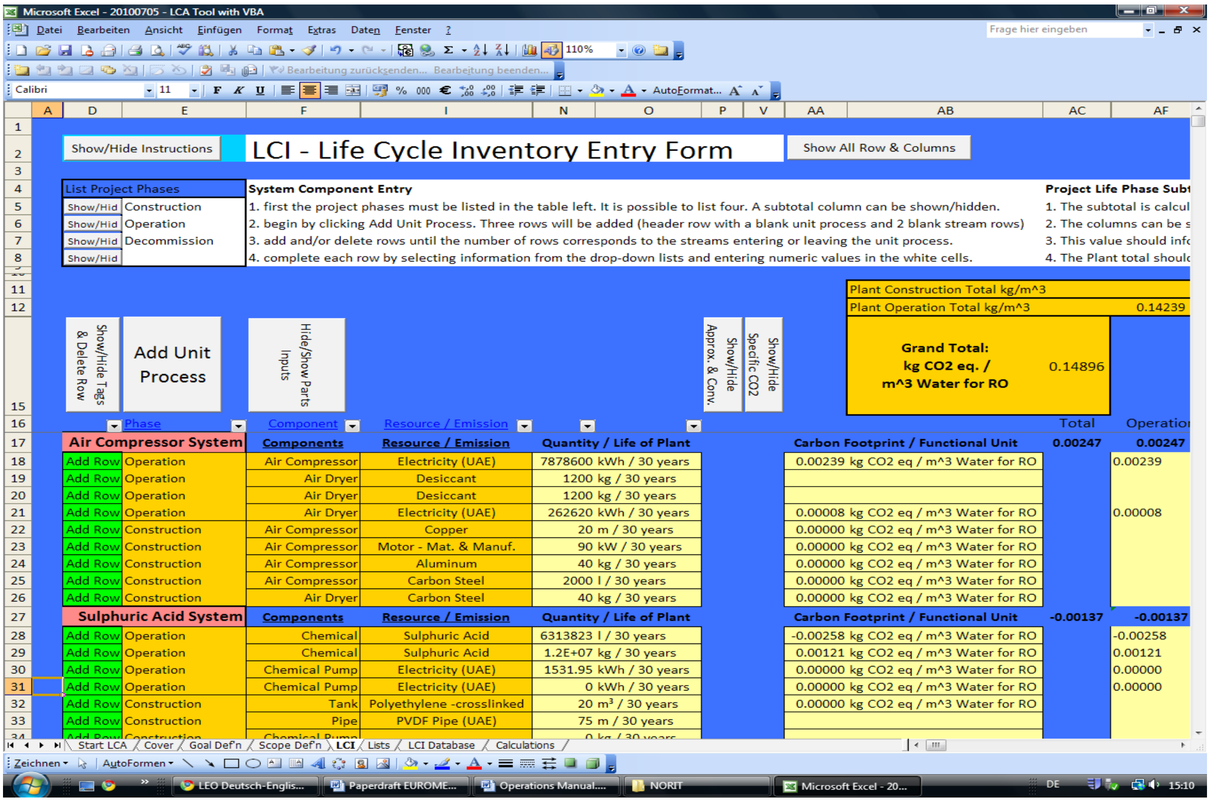
4.4.3 For which duration? How many years?

30

4.4.4 In which quality?

Suitable for RO filtration

Fig. 4. A screenshot of the Scope Definition worksheet in the CO_2 footprint computational tool.



LCI - Life Cycle Inventory Entry Form

List Project Phases
Construction
Operation
Decommission

System Component Entry
1. first the project phases must be listed in the table left. It is possible to list four. A subtotal column can be shown/hidden.
2. begin by clicking Add Unit Process. Three rows will be added (header row with a blank unit process and 2 blank stream rows)
3. add and/or delete rows until the number of rows corresponds to the streams entering or leaving the unit process.
4. complete each row by selecting information from the drop-down lists and entering numeric values in the white cells.

Project Life Phase Subt
1. The subtotal is calcul
2. The columns can be s
3. This value should info
4. The Plant total should

Plant Construction Total kg/m^3	
Plant Operation Total kg/m^3	0.14239
Grand Total: kg CO2 eq. / m^3 Water for RO	0.14896

Phase	Component	Resource / Emission		Carbon Footprint / Functional Unit	Total	Operation
Air Compressor System	Components	Resource / Emission	Quantity / Life of Plant	Carbon Footprint / Functional Unit	0.00247	0.00247
Operation	Air Compressor	Electricity (UAE)	7878600 kWh / 30 years	0.00239 kg CO2 eq / m^3 Water for RO		0.00239
Operation	Air Dryer	Desiccant	1200 kg / 30 years			
Operation	Air Dryer	Desiccant	1200 kg / 30 years			
Operation	Air Dryer	Electricity (UAE)	262620 kWh / 30 years	0.00008 kg CO2 eq / m^3 Water for RO		0.00008
Construction	Air Compressor	Copper	20 m / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		
Construction	Air Compressor	Motor - Mat. & Manuf.	90 kW / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		
Construction	Air Compressor	Aluminum	40 kg / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		
Construction	Air Compressor	Carbon Steel	2000 l / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		
Construction	Air Dryer	Carbon Steel	40 kg / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		
Sulphuric Acid System	Components	Resource / Emission	Quantity / Life of Plant	Carbon Footprint / Functional Unit	-0.00137	-0.00137
Operation	Chemical	Sulphuric Acid	6313823 l / 30 years	-0.00258 kg CO2 eq / m^3 Water for RO		-0.00258
Operation	Chemical	Sulphuric Acid	1.2E+07 kg / 30 years	0.00121 kg CO2 eq / m^3 Water for RO		0.00121
Operation	Chemical Pump	Electricity (UAE)	1531.95 kWh / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		0.00000
Operation	Chemical Pump	Electricity (UAE)	0 kWh / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		0.00000
Construction	Tank	Polyethylene -crosslinked	20 m³ / 30 years	0.00000 kg CO2 eq / m^3 Water for RO		
Construction	Pipe	PVDF Pipe (UAE)	75 m / 30 years			

Fig. 5. A screenshot of the Life Cycle Inventory worksheet in the CO_2 footprint computational tool.

Table 1
Inventory listing for the air compressor system (construction and operation only)

Components	Component parts	Items	Resource/emission	Quantity/item	Period	Quantity/life of plant
Air compressor	Energy	2	Electricity (UAE)	15 kWh	1 h	7878600 kWh/30 y
Air dryer	Influent	2	Desiccant	20 kg	1 y	1200 kg/30 y
Air dryer	Energy	2	Electricity (UAE)	0.5 kWh	1 h	262620 kWh/30 y
Air compressor	Tubing	1	Copper	20 m	30 y	20 m/30 y
Air compressor	Complete motor	2	Motor - mat. & manuf.	45 kW	30 y	90 kW/30 y
Air compressor	Casing	2	Aluminum	20 kg	30 y	40 kg/30 y
Air compressor	Receiver tank	1	Carbon steel	2000 l	30 y	2000 l/30 y
Air dryer	Housing	2	Carbon steel	20 kg	30 y	40 kg/30 ys

life, normalized according to the functional unit (with or without allocation) and the end result of the total carbon footprint is calculated. At this point the user can interpret and analyze the results.

The above mentioned methodology was carried out for the Palm Jumeirah case study and based on the gathered inventory information from the plant designers and operators as well as based on the internal database, the overall carbon footprint of one m³ of RO feed was calculated to have a value of 0.133 kg CO_2eq./m³. This amount closely resembles the common CO_2/km emissions of an average small car. The distribution of this value over the contributions of the different process components (including commissioning, operation and maintenance) is shown in Fig. 6. The major contribution to the carbon footprint (approx. 74%, mainly resulting from electricity consumption) are the seawater transfer pumps which are responsible for the mainline pressure enabling both the intake from the sea as well as the dead-end filtration in the UF modules. The second largest contribution (7.2%) comes from the backwash pumps and third largest from the membrane skids (4.6%). The travelling band screens are responsible for 4.4% of the emissions. Other contributions such as the ones resulting from the chlorination, straining or coagulation proved to be non meaningful in terms of CO_2eq. emissions.

Since it was clear at this point that the energy production was the lead player in the carbon emissions, a sensitivity analysis was performed regarding the energy source. For example by changing the electricity supply from natural gas (typical for the Arabian Gulf region) to a regenerative source such as wind massively reduces the carbon footprint to a level of 21 g CO_2 eq./m³ (84% reduction). The contribution of construction, production of chemicals and transportation then becomes more dominant as can be seen in Fig. 7.

Another sensitivity analysis was made on the life time of the UF membranes. Reducing it from 10 to 5 years led to an increase of the carbon footprint from 133 g to 139 g CO_2 eq./m³ RO feed. The partial contribution of the UF skids to the overall result was raised from 4.6% to 8.6%.

4. Conclusions and outlook

A new and easy to use carbon footprint calculation tool was successively created and populated with background

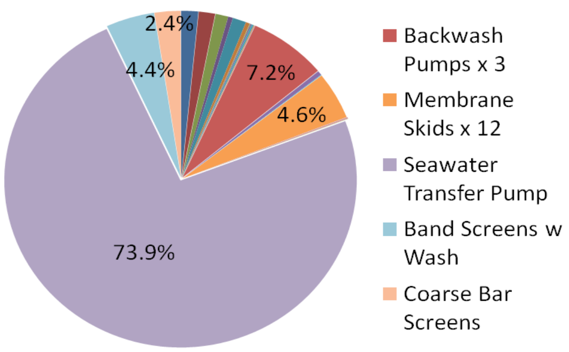


Fig. 6. The component contribution to the overall carbon footprint of 0.133 kg CO_2 eq./m³ RO feed.

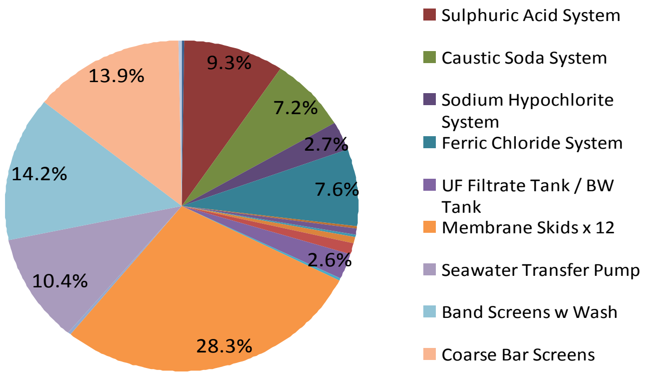


Fig. 7. The component contribution to a hypothetical case of using wind as the energy source (0.021 kg CO_2 eq./m³ RO feed).

Table 2
The tool's internal database specifically collected for membrane-based water treatment systems

Best approx resource/emission	Qty	Unit CO2 Footprint	Source
Steel, at plant + avg. work, kg	3.56	kg CO_2eq./kg steel, at plant + avg work	Ecoinvent
Austenitic stainless steel, kg	3.5882	kg CO2eq./kg austenitic stainless steel	Nickel Inst.
Copper tube, kg	0.98	kg CO_2eq /kg copper tube	Ecoinvent
Chromium steel, plant + avg. work, kg	6.96	kg CO_2eq./kg chromium steel, plant + avg work	Ecoinvent
Drawing of pipes, steel, kg	0.437	kg CO_2eq kg drawing of pipes, steel	Ecoinvent
Reinforcing steel, at plant, kg	1.48	kg CO_2eq/kg reinforcing steel, at plant	Ecoinvent
Cast iron, at plant, kg	1.52	kg CO_2eq./kg cast iron, at plant	Ecoinvent
Aluminum, at plant + avg. work, kg	11.74	kg CO_2eq. kg aluminum, at plant + avg work	Ecoinvent
Motor - mat. & manuf., kW	0.0362	kg CO_2eq./kW motor - mat. & manuf.	CPM Chalmers
HDPE pipe, kg	2.381	kg CO_2eq./kg HDPE pipe	GEMIS
HDPE, granulate, at plant, kg	1.95	kg CO_2eq./kg HDPE, granulate, at plant	Ecoinvent
LDPE, granulate, at plant, kg	2.1	kg CO_2eq./kg LDPE, granulate, at plant	Ecoinvent
GRP pipe, polyester, hand, kg	4.88	kg CO_2eq/kg GRP pipe, polyester, hand	Ecoinvent
GRP pipe, polyester, inj'n mould, kg	8.81	kg CO_2eq./kg GRP pipe, polyester, inj'n mould	Ecoinvent
PVC pipe, kg	2.5828	kg CO_2eq./kg PVC pipe	GEMIS
Ethylene, kg	1.7159	kg CO_2eq./kg ethylene	GEMIS
Polyvinyldenchloride, granulate, kg	4.92	kg CO_2eq./kg polyvinyldenchloride, granulate	Ecoinvent
Concrete, kg	9.47e-1	kg CO_2eq./kg concrete	GEMIS
Bisphenol A, powder, at plant, kg	4.88	kg CO_2eq./kg bisphenol A, powder, at plant	Ecoinvent
N-methyl 4-pyrrolidone, at plant, kg	3.95	kg CO_2eq./kg N-methyl 4-pyrrolidone, at plant	Ecoinvent
Glycerin, kg	9.5058	kg CO_2eq./kg glycerine	GEMIS
PUR foam – hard, kg	4.1935	kg CO_2eq./kg PUR foam - hard	GEMIS
PVC, cradle to regional storage, kg	2.01	kg CO_2eq./kg PVC, cradle to regional storage	Ecoinvent
Water, kg	0.0004	kg CO_2eq./kg water	GEMIS
Electricity mix NL, kWh	0.67	kg CO_2eq./kWh electricity mix NL	Ecoinvent
Natural gas (NL), TJ	6.40e04	kg CO_2eq./TJ natural gas (NL)	GEMIS
Calcium chloride, at plant, kg	0.854	kg CO_2eq./kg calcium chloride, at plant	Ecoinvent
Sodium hydroxide 50%, prod mix, kg	1.1000	kg CO_2eq./kg sodium hydroxide 50% prod mix	Ecoinvent
Sodium hypochlorite 15% in H_2O, kg	0.8880	kg CO_2eq./kg sodium hypochlorite 15% aq.	Ecoinvent
Hydrochloric acid 30% in H_2O, kg	0.8530	kg CO_2eq./kg hydrochloric acid 30% aq.	Ecoinvent
Iron (III) chloride 40% in H_2O, kg	0.8030	kg CO_2eq./kg iron (III) chloride 40% aq.	Ecoinvent
Sulphuric acid, at plant, kg	0.124	kg CO_2eq./kg sulphuric acid, at plant	Ecoinvent
Biocides, for paper, unspecified, kg	5.65	kg CO_2eq./kg biocides, for paper, unspecified	Ecoinvent
Chlorine dioxide, at plant, kg	6.24	kg CO_2eq./kg chlorine dioxide, at plant	Ecoinvent
Electricity from natural gas, kWh	0.5	kg CO_2eq./kWh electricity from natural gas	Ecoinvent
Waste to landfill (DE), kg	1.1234	kg CO_2eq./kg waste to landfill (DE)	GEMIS
Trans sea ship - Enschede-Dubai, kg	0.071	kg CO_2eq./kg trans sea ship - Enschede-Dubai	EcoTransIT
Trans sea ship - Shanghai-Dubai, kg	0.1017	kg CO_2eq./kg trans sea ship - Shanghai-Dubai	EcoTransIT

data especially relevant for water treatment processes. The tool was developed side by side with a case study from a UF SWRO pre-treatment in Palm Jumeirah using real operational data and resulted in a footprint of 0.133 kg CO_2eq. per m^3 of RO feed. The hot spots where major emission reduction improvements can be made are the electricity consumption of the seawater transfer pumps and (to a lesser extent) that of the backwash pumps. Changing the energy source to wind turbines would hypothetically reduce the carbon footprint by 84%.

The tool will be further developed and validated using commercial databases and LCA software. Another interesting aspect would be the comparison of the carbon footprint resulting from alternative pre-treatment process designs such as the use of media filters, beach-wells or different membrane brands. For a running plant with a fixed design the tool could be used to optimize the operation with respect to the carbon footprint and potentially integrated to a PLC system to achieve that using the control system.

Acknowledgments

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