National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Life Cycle Assessment of two drinking water production schemes

RIVM Letter report 2015-0209

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oasen
drinkwater

Colophon

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Levenscyclusanalyse van twee drinkwaterproductieprocessen

Met een zogeheten levenscyclusanalyse (LCA) is het mogelijk om te bepalen welke impact het productieproces van een product heeft op het milieu. De analyse omvat alle stadia die nodig zijn om een product te produceren en te consumeren, dus vanaf het onttrekken van de benodigde grondstoffen tot en met de verwerking van afval. Het doel van een LCA is om alternatieven te vergelijken en ‘hotspots’ in het productieproces in kaart te brengen, zodat het productieproces kan worden geoptimaliseerd. Het RIVM en drinkwaterbedrijf Oasen hebben een LCA uitgevoerd van twee drinkwaterproductieprocessen: een conventionele en een alternatieve.

Bij drinkwaterproductiebedrijven kunnen verschillende technieken worden ingezet om van oppervlaktewater en grondwater drinkwater te maken. De keuze van de technieken is afhankelijk van de kwaliteit van het bronwater. Membraanfiltratie is een techniek waarmee kan worden geanticipeerd op schommelingen in de kwaliteit van het bronwater. Dit is van belang omdat de kwaliteit van de drinkwaterbronnen uit oppervlaktewater naar verwachting in de toekomst onder druk staat. Membraanfiltratie is daardoor aantrekkelijk om voor drinkwaterproductie te worden gebruikt, alleen gaat deze techniek gepaard met een hoog energieverbruik.

In deze LCA is onderzocht wat de invloed van dit energiegebruik is ten opzichte van de andere onderdelen van het drinkwaterproductieproces. Daarnaast is gekeken hoe dit verandert als alleen windenergie wordt gebruikt bij de productie in plaats van de standaardenergiemix van Nederland. Wanneer uitsluitend windenergie wordt gebruikt, lijkt membraanfiltratie niet slechter voor het milieu dan een conventioneel drinkwaterproductieproces. Deze uitkomst is sterk afhankelijk van de mate waarin de werkwijze van de leveranciers van de benodigde hulpstoffen duurzaam is.

Kernwoorden: drinkwater, levenscyclusanalyse, LCA, membraanfiltratie

Synopsis

Life Cycle Assessment of two drinking water production schemes

The RIVM and drinking water utility Oasen performed a life cycle assessment (LCA) of two alternative drinking water production schemes. The LCA provides insight in where in the production process the highest environmental impacts take place. An LCA covers the impact in the whole life cycle of a product or process. Thus from cradle (extraction of resources) to gate (produced product) or grave (disposal of product). In order to anticipate a changing quality of drinking water sources, using membrane filtration as a basis for the drinking water production could be attractive. However, this technique has a high energy demand. This LCA provides insight in the impact of that energy demand, compared to the impact of the other parts of the process. Furthermore, it is analysed how this impact changes when wind energy is used instead of the country mix. In that case, membrane filtration seems to have a comparable impact on the environment as the conventional alternative to produce drinking water. This result strongly depends on the production processes of the suppliers of substances required for the drinking water production.

Keywords: drinking water, life cycle assessment, LCA, membrane filtration

Contents

Summary

The goal of this study was to perform a life cycle assessment (LCA) of a new drinking water production process that is in its development phase and an alternative production process. The functional unit was the perceived year production of drinking water with a quality that meets the company standards. The scope was cradle to gate, thus from resources needed to the point the water enters the distribution networks. Primary data was gathered on the processes at the production plant and the waste water treatment plant, most other processes (production chemicals used in the process etc.) where based on European average secondary data (ecoinvent and literature). The results showed that the two alternatives have a comparable impact score. The new process, that is based on membrane filtration, scores better in two of the impact categories (acidification and human toxicity) and comparable in the other impact categories. The results are subject of change, because the production process is still under development and new technical insights or data will change the model built and thus the results. Performing a LCA in this phase of development provides insight in the hotspots and supports choices on the focus of improvements.

1 Introduction

Drinking water utility Oasen is designing a new drinking water treatment process for their drinking water production plant at Kamerik. They are testing a treatment process with a central role for membrane filtration, seeking for a process that produces drinking water of an impeccable quality, which moreover is independent of changes in quality of the drinking water source. Although Oasens ideal is that sources of drinking water are protected and will increase in quality, like the EU Water Framework (1) prescribes, she also wants to pro-actively anticipate on possible changes in that quality, e.g. due to climate change and/or social demographic changes (2, 3).

Oasen has the following mission: “Drinking water is available for the Oasen-customer at any time, now and in the future, with a quality that is best for human health and a production and distribution process that is best for the environment”. Environment is defined broad and life cycle thinking mentioned as an important element in deciding what is best for the environment.

Membrane filtration is known for its high energy demand. In order to compare the impact of this energy demand with impacts of other parts of the drinking water production process and with an alternative drinking water production scheme, a life cycle assessment (LCA) was performed. The LCA can also provide insight in the hotspots of the perceived production scheme, and thus on the optimal design from the perspective of environmental impact. A challenge for LCAs of processes or products in the developing stage is the lack of data on how a full-scale operation will perform.

2 Goal and Scope

2.1 Goal and target group

The goal of this study was to compare the environmental impact of two drinking water treatment processes from a life cycle perspective. The results can support the drinking water utility Oasen in their decision and design process towards a new drinking water production plant at Kamerik. The drinking water process that is now tested by Oasen was compared with a more conventional treatment process. The design of both alternatives was based on state of the art knowledge of water treatment technologies. The results can be used to compare the impacts of the two alternatives, but also to analyze the contribution of the different steps of the alternatives (hotspot analyses). The results are for intern use by the drinking water utility. Because production processes are analyzed that are under development, the LCA will be under development as well. Results presented in this report may alter soon because of new technical insights. The goal is not to give a final judgement on the impact of the two production processes but to contribute to the development of new production processes by showing where the environmental hotspots are and how they differ between alternatives.

2.2 Function, functional unit and reference flows

The function of the object under study is to produce drinking water that meets the company standards of Oasen: as low as possible degree of hardness and color-intensity, chemical and biological stable, and twice as low as the Dutch standards for prioritaire substances.
The functional unit is a year production of 2.400.000 m^3 drinking water that meets the company standards. Thus the reference flows that are compared in this study are

- 2.400.000 m^3/year drinking water produced from groundwater (river bank infiltrate) produced by a high standard conventional drinking water production scheme; and
- 2.400.000 m^3/year drinking water produced from groundwater (river bank infiltrate) produced by a high standard membrane filtration based drinking water production scheme.

2.3 Description of production schemes

General

The production plant is located at Kamerik (Figure 1a). The abstraction wells are close to the plant alongside the river. Drinking water produced at Kamerik is delivered in the region marked in Figure 1b.

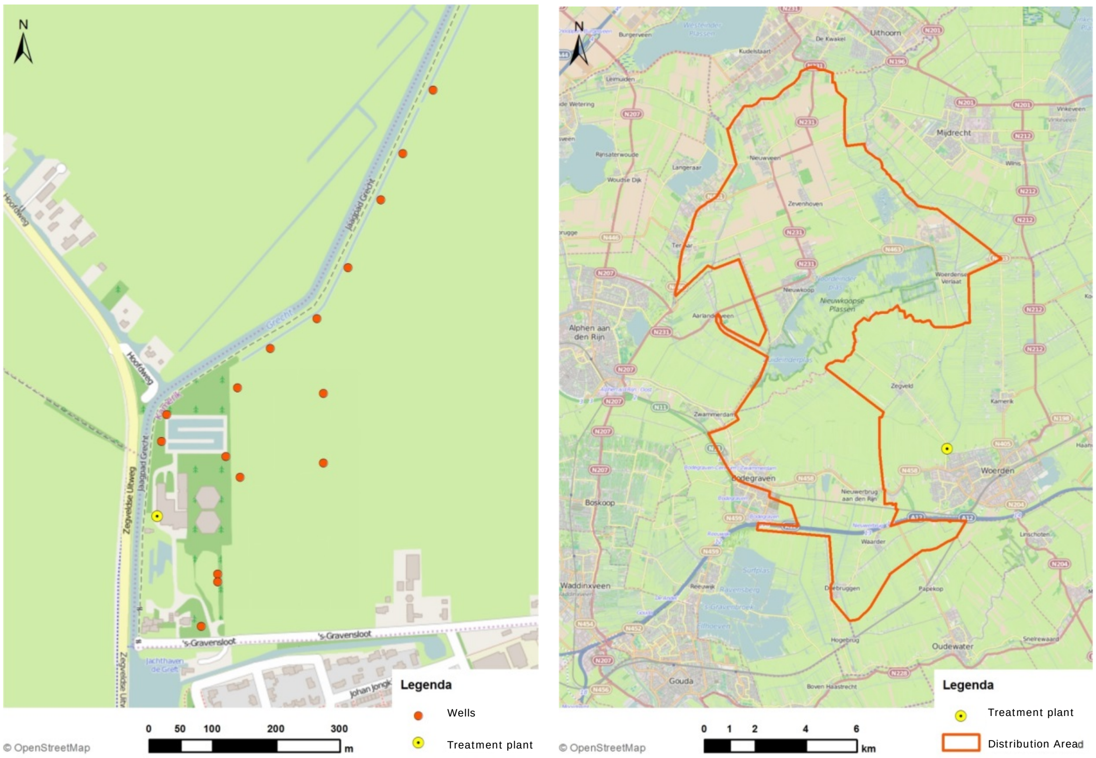


Figure 1 A) Plant and abstraction wells at Kamerik; B) Region that depends on drinking water production at Kamerik.

Conventional scheme

The scheme of the conventional production process modeled consists of the following steps:

1. Abstract water (river bank infiltrate) and transport to the production plant
2. Biological iron removal with dry filtration (oxygenation and rapid sand filters)
3. Softening
4. Carry over filter
5. Ion exchange
6. Activated carbon
7. Disinfection with UV

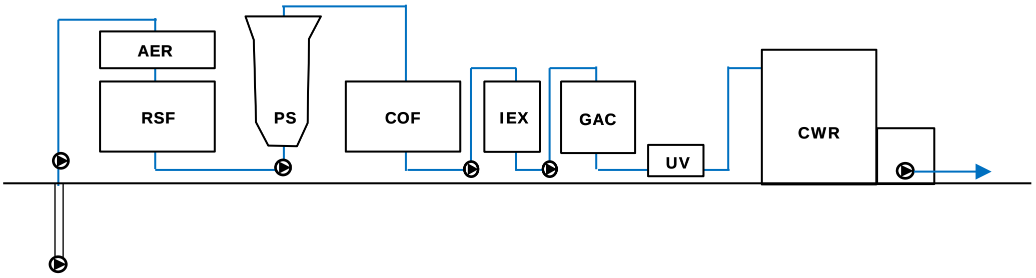


Figure 2. High standard conventional production process. AER and RSF: Aeration and Rapid Sand Filtration (biological iron removal); PS: Pellet Softening; COF: Carry-Over filter; IEX: Ion exchange; GAC: Granular Activated carbon; UV: disinfection with UV; CWR: Clean Water Reservoir.

Membrane filtration (MF) scheme

The scheme of the MF production process modeled consists of the following steps:

- Abstract water (river bank infiltrate) and transport to the production plant
- Membrane filtration (includes pump)
- Ion Exchange
- Remineralization (includes pump)
- Oxygenation and degasification

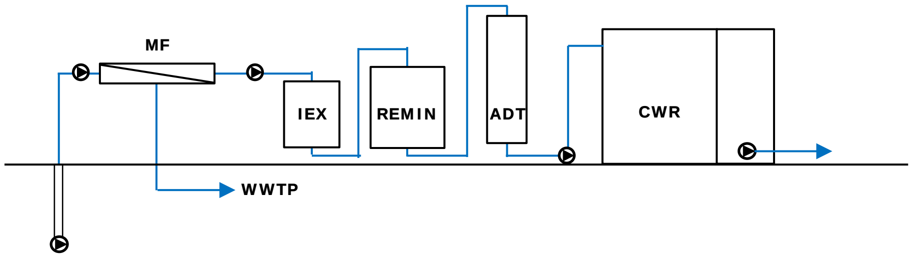


Figure 3. Membrane filtration based production scheme. MF = membrane filtration; WWTP: waste water treatment plant; IEX: ion exchange; REMIN: remineralisation; ADT: Aeration and Degasification Tower; CWF: Clean Water Reservoir

2.4 System boundaries

A cradle to gate analysis was performed, since it is assumed that the two alternatives have comparable impacts from gate to grave. This however, is under investigation of Oasen, because the MF alternative produces drinking water with another quality than the present quality, and thus the transport to the consumer and the results of using the water might change compared to common practice (less scaling etc.). The research is however not yet in a stage that it can be anticipated on in this study.

The construction and dismantling of the infrastructure of the production plant and abstraction wells (pipes, pumps, buildings, reservoirs, etcetera) were left out of the scope of this project. It is assumed that their impact per functional unit will be small, because their relative long time of functionality. This assumption is more often used for drinking water production LCAs (4-7) and shown to hold in other studies (4, 8-11).
Thus, the study focusses on the use of energy, chemicals and materials during the treatment process, including cleaning of the systems, processing waste streams and transport of the chemicals and materials.

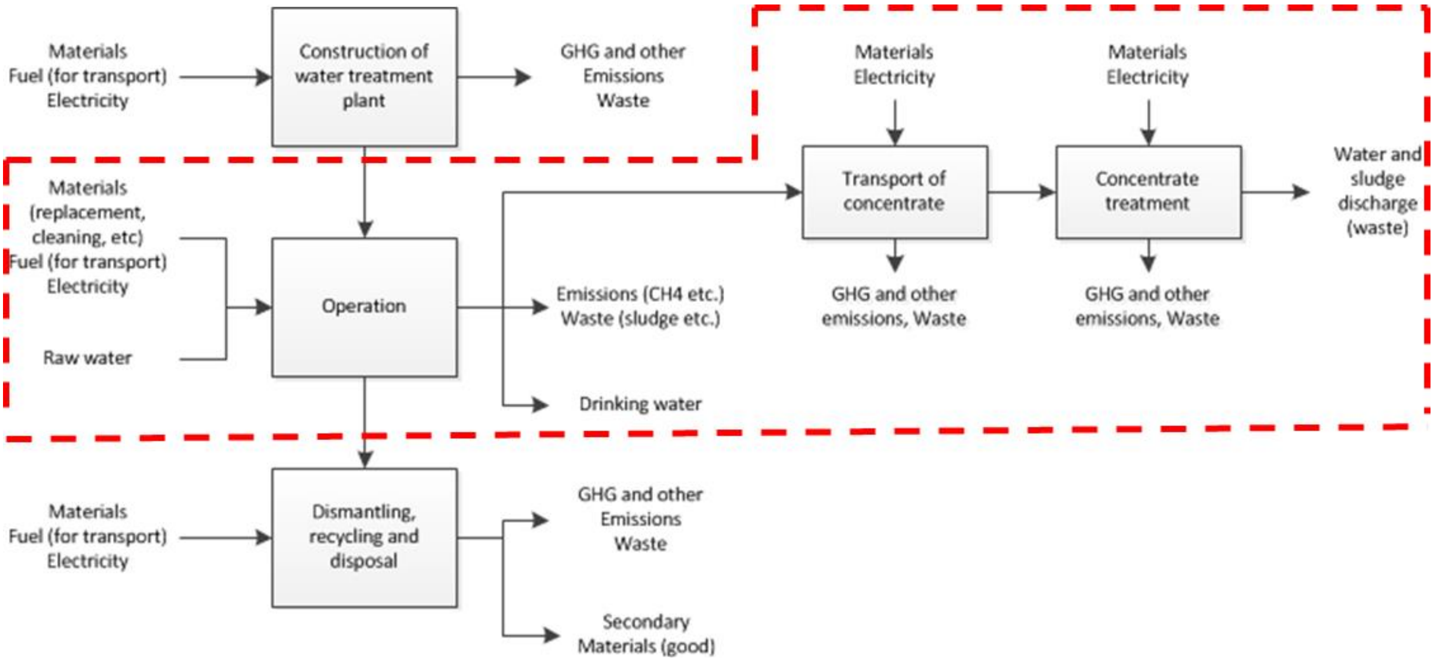


Figure 4: Visualization of system boundaries (dotted red line)

Direct emissions to the environment during the production phase are:

- Methane emissions and carbon dioxide emissions during the oxygenation and degasification phase.
- Hydrogen peroxide during regeneration of the wells.

The latter is neglected because the chemical is degraded/ not active anymore after the regeneration process.

In the membrane filtration scenario, the concentrate is transported to a waste water treatment plant (WWTP), which treats the stream as regular wastewater and directs the treated water back into the river. Given the present quality of the water used by Oasen at Kamerik, the sludge produced by the WWTP will hold significantly altered concentrations of PO_4, NH_4 and Fe, but the resulting water effluent of the WWTP into surface water, will not change. In other words, all the substances that change the quality of the effluent of the WWTP are bound to the sludge, that, in the end, is incinerated, which is included in the LCA.
In addition, the indirect emissions and resources of the background system were taken into account, a.o. electricity production, production and transport of chemicals and materials (Figure 4).

2.5 System expansion and allocation

In this study, the production schemes under investigation were assumed to provide no additional functions or products which would require expansion of the system boundaries. The conventional scheme has by-products, pebbles, which is a rest stream that is functionally used as a product with economic value: insulation material and a lime applicant for gardens. The transport and processing of this stream was allocated to the new function, but the ‘production’ of the rest stream was allocated to the drinking water treatment process. Energy recovery was foreseen from plastic incineration and biogas generation from the sludge. The total energy use is compensated for this energy recovery.

2.6 Data quality

As far as possible, data on the core system is based on present process data (e.g. chemical dosing, electricity demand, cleaning strategies etc.); experience/expertise within Oasen and, when totally new, consultation of the companies that supply relevant parts of the treatment process (e.g. the remineralisation process). Background data for electricity, chemicals and materials were related to average country specific conditions of the countries where the used chemicals/ materials were produced (e.g. electricity, disposal etc.) or else average European conditions.
For the chemicals and materials for which we could not find satisfying data in existing databases, new treatment processes were modeled based on data provided by the manufactures.

Table 1 shows per datatype the source of the data, which indirectly gives an indication of the quality. Because of the prospective nature of the study (the treatment processes are not yet operating at full scale), the ranges for the uncertainty assessment were hard to quantify for some aspects. When we only apply uncertainty assessment on the elements we do know, the ranges may result in asymmetric results which are questionable.

A sensitivity analysis was performed on the primary data. Minima and maxima of these variables were estimated by experts from Oasen and formed the basis of the sensitivity analysis. All variables were assessed using a triangular distribution and 1000 iterations with Latin Hypercube sampling.

Table 1: Sources of data

Process	Alternative	Data source	Extrapolation from
Abstraction and transport to Kamerik (pumping and regeneration)	Both	Oasen	Present process data
Biological iron removal (including back wash)	Conventional	Oasen	Test installation
Softening	Conventional	Oasen	Present process data
Carry Over Filter (including back wash)	Conventional	Oasen	Present process data
IEX	Conventional and MF	Manufacturer	Average process data provided by manufacturer
Active carbon filter	Conventional	Oasen	Present process data

Process	Alternative	Data source	Extrapolation from
UV	Conventional and MF	Oasen	Present process data
Membrane filtration	MF	Oasen	Test-installation
Remineralisation	MF	Oasen/ manufacturers (compare three systems)	Test-installation and average process data provided by manufacturer
Oxygenation and degassification	MF	Oasen	Present process data

2.7 Life cycle impact assessment

The LCIA method ReCiPe (12) was used to translate emissions and use of resources into impacts at midpoint level. Midpoints are the impacts that indicate a problem that eventually contribute to the impacts at endpoint, e.g. ozone depletion and climate change. Endpoint is defined as: at the end of the cause-effect chain and represents the impact on what we aim to sustain (biodiversity, human health, resources). In this study, we used midpoint to be able to investigate in more detail to which environmental effects the activities contribute. Table 2 lists the selected impact categories.

Table 2 LCimpact categories used in this study

Category	Unit	Explanation
Global warming	$kgCO_{2eq}$	Impact on global climate change due to emissions of greenhouse gasses like CO_2, CH_4 and N_2O
Acidification	$kgSO_{2eq}$	of terrestrial ecosystems due to atmospheric acid forming pollutants
Eutrophication	Peq	of fresh waters due to P emissions
Human toxicity	$1{,}4DB_{eq}$	1,4 dichloorbenzene, incidences of diseases due to emissions of toxic substances
Freshwater aquatic ecotoxicity	$1{,}4DB_{eq}$	1,4 dichloorbenzene, potential disappeared fraction of freshwater species due to emissions of toxic substances
Cumulative energy demand	MJ	Overall energy demand

3 Life cycle inventory

The inventory is given in this report as explicit as possible in order to be able to discuss, improve and recalculate the results.

3.1 Membrane filtration variant

Table 3: Inventory of the Membrane Filtration variant.

What	**How much**	**Unit**	**Remarks**	**Source**
Abstraction and transport				
Water	3.000.000	m^3	Recovery of 80%	Scenario
Energy (pump)	570.000	kWh	0.19 kWh/m3	Present Process
Hydrogen peroxide	1200	Liter	Regeneration of 10 wells every 5 years 600l. per generation	Present Process
Membrane filtration				
Energy (pump)	1.200.000	kWh	10 bar; efficiency of 70%	Test installation/ other installations
Antiscalant	6,25	Ton	2.5 g/m3	Literature
Citric acid	1200	Liter	2 per year a CIP; 60L. per stack, 10 stacks	Other installations
Sodium Hydroxide	1200	Liter	2 per year a CIP; 60L. per stack, 10 stacks	Other installations
Natrium Bilsulfite	4800	Liter	6 per year a CIP; 80L. per stack, 10 stacks	Other installations
Membrane (ESPA2; Polyamide)	1	Ton	Lifespan of 5a. Flux: 1m3/module/hr; peak factor: 1.4; 10kg per module; also disposal	Test installation
Concentrate	600000	m^3	Recovery of 80%	Test installation
Treating the concentrate				
Energy (pump)	29.000	kWh	1.2 bar; rendement of 70%	Based on present process
Energy (WWTP)	168.000	kWh	$0.28/m^3$	Present process
Renewed energy biogas from sludge	60.500	kWh	36% of total energy use	Present process
Polyelectrolyte	0,01	Ton	2 g/kg sludge (dry)	Present process

What	How much	Unit	Remarks	Source
Sludge produced	108	Ton	0.18 kg/m3	Present process
Sludge to incineration	19	Ton	After water withdrawal from 4% to 23% dry matter content	Present process
Ion Exchange				
Energy (pump)	114.000	kWh	1.2 bar; rendement of 70%	Based on present process
Resin	2,3	Ton	Installation needs 30 m^3 resin, replace every 10 year; 750 kg/m3	Other installations
HCl	14,6	Ton	Regeneration of resin	Other installations
Energy	78	kWh	Regeneration of resin	Other installations
Remineralisation (Granular Calcite)				
Granular Calcite	240	Ton	1 mol/m3	Drinking water standard
CO_2	634	Ton	6 mol/m3; transport weight is 857 ton	Test installation
Energy (Back wash)	8.000	kWh	0.66 kW/m3	Test installation
Oxygenation and degasification				
Energy	312.000	kWh	0.13 kW/m^3	Present Process
Emissions of CH4	4.8	Ton	2 mg/l to air	Present Process
Emmissions of CO2	317	Ton	3 mol/m^3	Test installation
Disinfection with UV (optional)				
Energy	140.000	kWh	8 lamps; 2 kW/lamp	Other installation
UV lamps	32	Kg	8 lamps; 4 kg each; also disposal	Other installation and literature

3.2 Conventional variant

Table 4: Inventory of the conventional variant.

What	How much	Unit	Remarks	Source
Abstraction and transport				
Water	2.500.000	m^3		Scenario
Energy (pump)	480.000	kWh	0.19 kWh/m3	Present Process
Hydrogen peroxide	1200	Liter	Regeneration of 10 wells every 5 years 600l. per generation	Present Process

What	**How much**	**Unit**	**Remarks**	**Source**
Biological iron removal				
Energy (oxygenation)	312.000	kWh	0.13 kWh/m3	Present process
Sand	44	Ton	25m^3 water per bed per hour; 50m^3 sand per bed; sand weights 1600 kg/m^3; after 20 years renewal of bed.	Test installation
Energy (Back wash)	16.000	kWh	0.66 kW/m3	Present process
Ch4 emissions	4.8	Ton	2 mg/l	Present process
Softening				
Sodium Hydroxide	480	Ton	200 ton/Mm^3	Present process
Sulfuric Acid	480	Ton	200 ton/Mm^3	Present process
Sand	83	Ton	40 ton/Mm^3	Present process
Pellets	710	Ton	0.3 kg/m3; Disposal → reuse as, a.o. insulation material	Present process
Carry Over filter				
Sand	44	Ton	25m^3 water per bed per hour; 50m^3 sand per bed; sand weights 1600 kg/m^3; after 20 years renewal of bed.	Test installation
Energy (Back wash)	47.000	kWh	0.66 kW/m^3	Present process
Sludge	257	Ton		
Ion Exchange				
Resin	2.3	Ton	Installation needs 30 m^3 resin, replace every 10 year; 750 kg/m^3	Other installations
HCl	14.6	Ton	Regeneration of resin	Other installations
Energy	78	kWh	Regeneration of resin	Other installations
Waste water	1630	m^3	To WWTP	Other installations
Active carbon				
New active carbon	5	Ton	1m^3 AC filters 37.500 m^3 water; 1 m^3 AC weights 400 kg; 15% loss of AC during regeneration of AC and 5% due to back washing.	Other installations
Regeneration active carbon	26	Ton	1m^3 AC filters 37.500 m^3 water; 1 m^3 AC weights 400 kg; 15% loss of AC during regeneration of AC and 5% due to back	Other installations and literature

What	How much	Unit	Remarks	Source
			washing.	
Disinfection with UV				
Energy	140.000	kWh	8 lamps; 2 kW/lamp	Other installation
UV lamps	32	Kg	8 lamps; 4 kg each; also disposal	Other installation and literature

3.3 Background processes

3.3.1 *Electricity*

Electricity was modeled with the for The Netherlands specific electricity mix of the Ecoinvent database. However, Oasen holds a Green Energy Certificate of EON, which is covered by wind energy by EON. For the LCA, we modeled wind electricity based on the wind electricity mix in Dutch electricity mix in Ecoinvent. It is assumed that all processes outside the production plant (production chemicals, waste treatment RWZI etcetera use the country specific electricity mix. The way we modeled wind energy is not entirely ISO proof. E.g. ISO 14067 on carbon footprints does not allow compensation of ‘green certificates’. In order not to create an offset (double count of the wind energy produced in the Netherlands), the electricity mix for the Netherlands could be corrected for the wind-energy claim of Oasen. Compared to the total produced amount of wind energy in the Netherlands (29.000 megawatt in 2014), the use of Oasen is so small that for this study it was not considered necessary to compensate for this offset.

3.3.2 *Transport*

Transport for most materials and chemicals were modeled with the lorry 16-32t, EURO 5 from the Ecoinvent database. It describes average resource demand and emissions from operation (neglecting construction of truck and road infrastructure) depending on weight and transport distance.

Transport of materials and chemicals that come from overseas were modeled with the freight, sea, transoceanic tanker from the eco-invent database.

Transport distances were as much as possible based on primary data. Part of the transport distances could only be retrieved to the wholesale headquarters location, which is not necessarily the production location.

Table 5 Transport distance per material/chemical/disposal

Chemical/ Material	Distance (km)	Overseas?	Remarks
Hydro peroxide	90		Apeldoorn (wholesale)
Sand	80		East Groningen
Sodium hydroxide	180		Brussels (wholesale)
Sulfuric Acid	90		Apeldoorn (wholesale)
IEX resin	700		Production location Germany
Active Carbon new	700		Production location Jacobi in France
Active Carbon	600		Regeneration plant in

Chemical/ Material	**Distance (km)**	**Overseas?**	**Remarks**
regeneration			Germany
UV lights	100		Nuenen (wholesale)
Membranes	30.000	Yes	California
Citric acid	90		Apeldoorn (wholesale)
Sodium bisulfate	90		Apeldoorn (wholesale)
Anti scalant	450		New Port, England
Granular calcite	500		Site in Germany
Micronized calcite	500		Site in Germaby
CO2	150		Antwerpen (wholesale)
Calcium hydroxide	240		Wanze
Incinerator	50		Brabant
Sludge incinerator	50		Brabant
Sludge gas retrieval	20		Nijmegen

3.3.3 *Chemicals and material*

Table 6 reference to data for chemicals/materials + sources

Chemical/ Material	
Hydro peroxide	Conform STOWA 2012-06: Hydrogen peroxide, 50% in H2O plant (RER)
Sand	Conform STOWA 2012-06: Per ton: 1 ton Silica sand, 7.5 kWh electricity, 0.19 MJ heat.
Sodium hydroxide	Conform STOWA 2012-06: Sodium Hydroxide, 50% in H2O, membrane cell, at plant (RER)
Sulfuric Acid	Conform STOWA 2012-06: Sulphuric acid, liquid, at plant (RER)
IEX resin	Cationic resin CH
Active Carbon (AC) new	Conform STOWA 2012-06: For 1 kg AC: 3 kg hard coal, 1.6 kwh electricity, 12 kg steam and 0.33 m3 natural gas
Active Carbon regeneration	Conform STOWA 2012-06: Same as AC, but without hard coal
UV lights	96% glass, 2% steel, 2% copper, 30 mg mercury per lamp; disposal includes recovery of mercury (13)
Membranes	Glass fibre reinforced plastic, polyamide, injection moulded, global market; Extrusion, global market. (9)
Citric acid	Citric acid, global market
Sodium bisulfate	Sodium sulfite, global market
Anti scalant	Conform STOWA 2012-06: Polycarboxylates, 40% active substance at plant (RER)
Polyelectrolyte	Modeled conform STOWA 2012-06 as polyacrylamide homopolymeer
Granular calcite	Calcium carbonate > 63 microns, production, at plant EU-27

Chemical / Material	
Micronized calcite	Calcium carbonate > 63 microns, production, at plant EU-27
CO2	Carbon dioxide liquid, at plant (RER)
Calcium hydroxide	Modeled based on data of manufacturer
Incinerator membrane	Waste incineration of plastics (PE, PP, PS, PB), EU-27
Sludge incinerator	Modeled based on Afman and Korving (14)
Sludge gas retrieval	Modeled based on data of manufacturer

4 Results

4.1 Membrane filtration compared to conventional

A comparison of all impact categories is summarized in Figure 5, normalized against the scenario with the highest impact. It reveals that, when using wind energy, the membrane filtration variant scores better than the conventional high standard variant on most impact categories except for eutrophication. The production process of liquid CO_2 has the largest contribution to eutrophication.

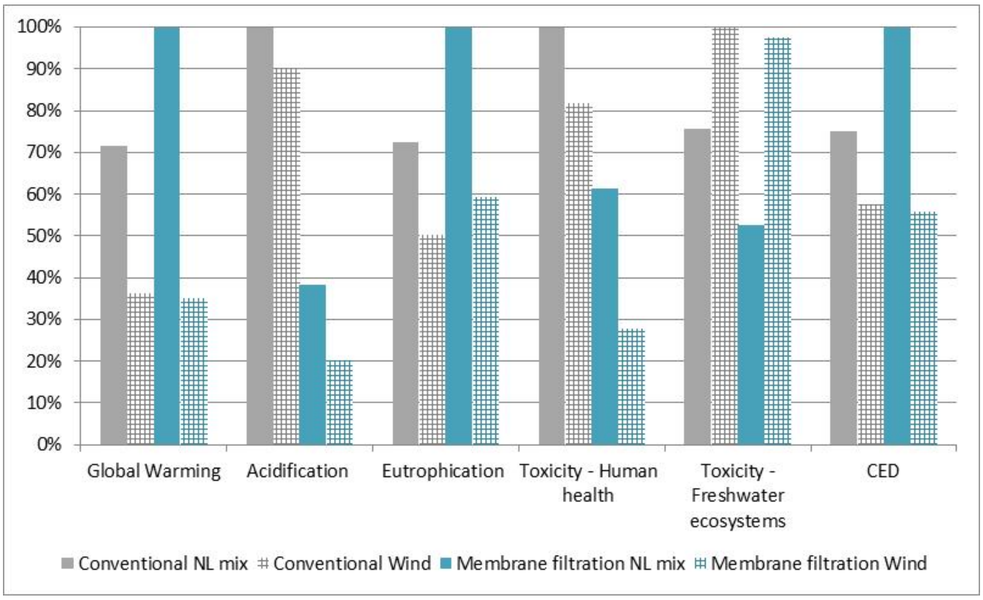
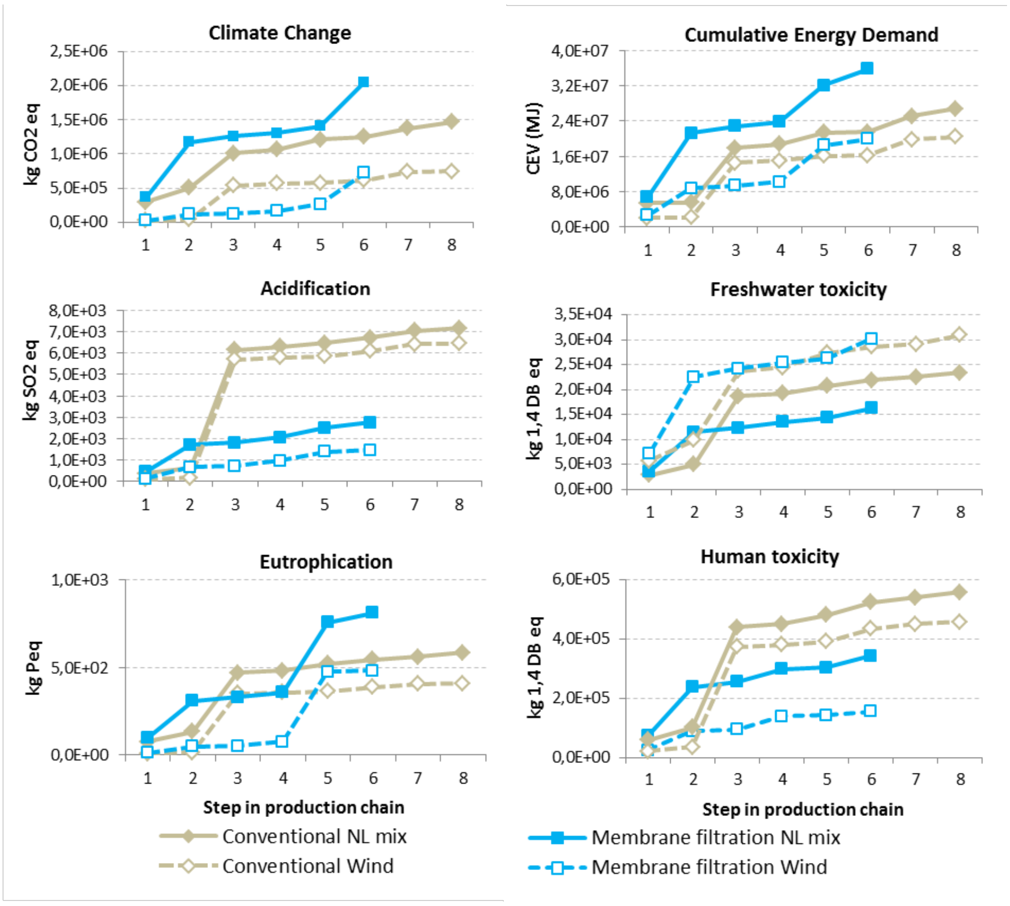


Figure 5 Comparison of the two alternatives with the two different electricity sources NL mix and wind electricity, relative to the scenario with the highest impact for that category; CED = cumulative energy demand.

Cumulative energy demand

The impacts per impact category per scenario are visualized in Figure 6. Energy demand is largely driven by the second production step (the membrane filtration) for the membrane filtration variant, which is largely reduced by using wind energy. The largest energy demand for the conventional variant is in the third step, which is softening. Changing from the Dutch NL mix to wind energy has a higher impact on the membrane filtration variant than on the conventional variant, because the latter process depends more on chemicals that are produced elsewhere. Particularly, production of NaOH has a large energy demand. Both alternatives end up with comparable energy demand when using electricity from wind at the drinking water production plant.



Figuur 6 Impact on climate change, acidification, toxicity for humans and fresh water ecosystems, eutrophication and the cummulative energy demand of the two production scenarios (membrane filtration and conventional high standard) and the two energy sources (Dutch country mix and windenergy) of the production of 2.4 milliion m^3 drinking water. The x-axis reflects the production steps and corresponds with Figures 2 and 3.

Climate change

The carbon footprint per production step shows a comparable pattern and conclusion as the Cumulative Energy Demand (CED). In the fourth step (oxygenation and degasification), the carbon footprint of the membrane variant rises largely due to emissions of CH_4 and CO_2 at the plant (the degasification part), which is the largest contributor to this impact category (Figure 7).

Acidification

Emissions during production and use of chemicals that are needed for the softening step, especially sulfuric acid, contribute most to acidification. Acidification is further caused by transport (25%) and electricity use (28%, see Figure 7).

Human toxicity

Emissions during production and use of chemicals that are needed for the softening step, especially sulfuric acid, contribute most to human toxicity (conventional variant only). For the membrane filtration variant, human toxicity is largely driven by energy use.

Fresh water ecotoxicity
The use of wind energy increases the impact on freshwater ecotoxicity. This is due to emissions of metals, which, because of their long residence time in the environment, are estimated to have relative large impacts on species. Furthermore, the chemicals used at the softening step (3) of the conventional variant contribute relatively much to the ecotoxicological impact.

Eutrophication
Eutrophication is largely driven by the production of liquid CO_2.

Contribution analysis
The contribution analysis of the membrane filtration variant (Figure 7) and the conventional variant (Figure 8) differ considerably. Most impacts of the conventional variant are largely driven by production of the chemicals and materials used during the treatment process. Especially the production of sodium hydroxide shows to have a significant contribution to the total impact for most impact categories and sulfuric acid to acidification and toxicity.

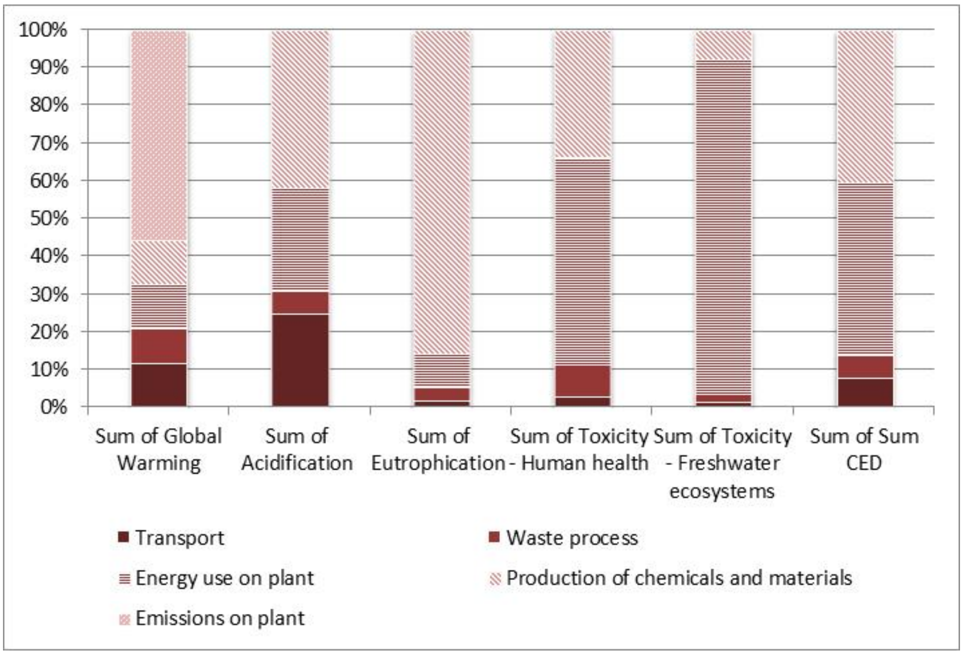


Figure 7. Contribution analysis of various processes in the membrane filtration scenario (wind energy).

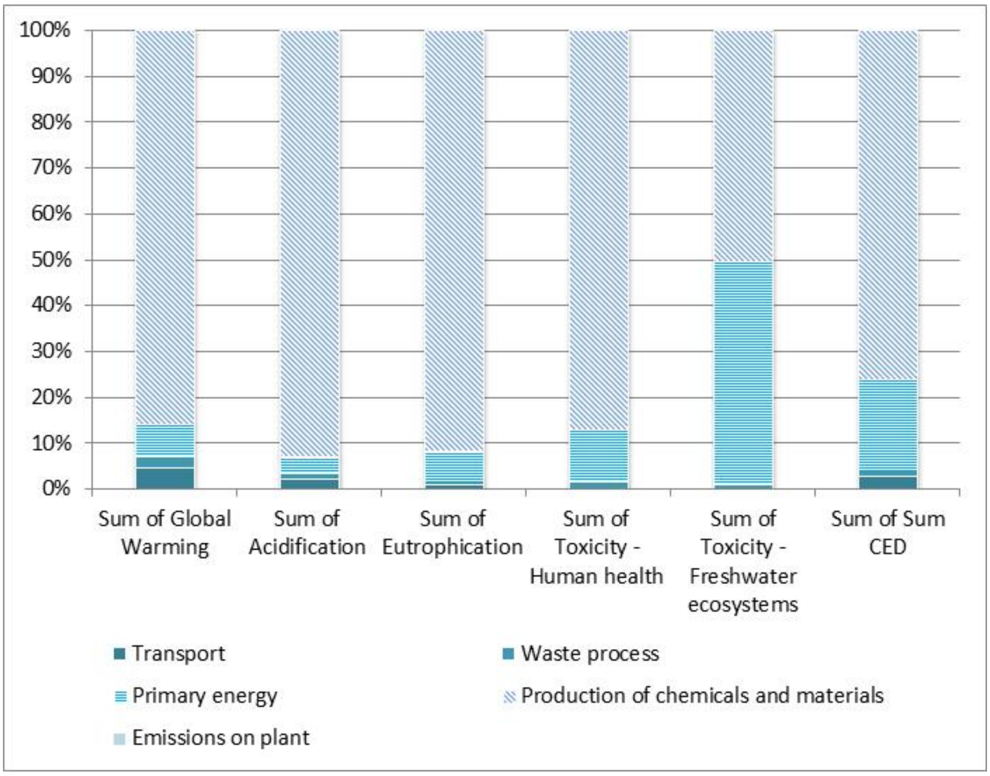


Figure 8. Contribution analysis of various processes in the conventional scenario (wind energy).

4.2 Results of sensitivity analyses

A sensitivity analysis has been performed by varying the variables between minima and maxima based on expert judgement of Oasen experts. Figure 9 shows the results of this sensitivity analysis for the three impact categories for which the differences between the two variants are small: climate change, fresh water ecotoxicity and eutrophication. The results show that the two variants do not differ significantly based on this analyses. Uncertainties in the background processes and LCIA characterization factors are not taken into account, but would only increase the uncertainty margins and thus support the conclusion that there is no significant difference between the impacts of these two variants.
For the membrane filtration variant, the results are most sensitive for the chosen recovery for all impact categories. The impact of the conventional variant (with wind energy) is most sensitive for the NaOH dosing.

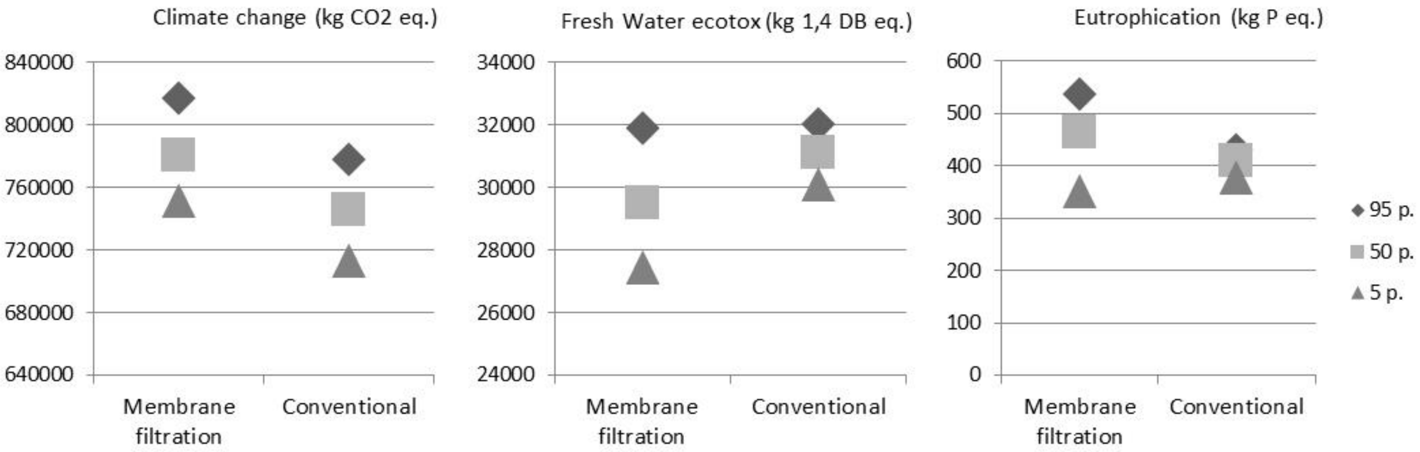


Figure 9. 5th, 50th and 95th percentile of the uncertainty distribution for the three impact categories where the differences between the two variants were small.

5 Discussion

Compare the two variants
The membrane filtration variant is estimated to have less (acidification, human toxicity) or a comparable (climate change, fresh water ecotoxicity, eutrophication and CED) impact compared to the high standard conventional variant when taking into account procurement of wind energy instead of the Dutch electricity mix.

The impact of the conventional variant is largely indirect, via purchase of chemicals, while the impact of the membrane filtration variant is largely driven by direct energy use and emissions at the plant.

Oasen considers adding UV to the production process of the membrane filtration variant. The conclusions of this report will not change significantly by adding that step.

Hotspots conventional variant
The use of chemicals produced elsewhere determine the impact. Especially the production of NaOH and sulfuric acid. Using supplier specific data instead of the secondary data that are used in this study, will improve the assessment and potentially change the results. For example, we used European average production data on NaOH production, but it could be possible that the NaOH supplier of Oasen uses a sustainable energy source. In that case, the hotspot might shift to another process in the life cycle, such as transport or to production of another additive.

Hotspots membrane filtration variant
The emission of CO_2 and CH_4 during the degasification phase and the purchase of liquid CO_2 contribute significant to climate change and eutrophication. Catching these emissions and reuse the CO_2 part in the production process might reduce these impacts when observed from a life cycle perspective. It would also save on required transport.

Sensitivity
The study is prospective. The gathered data may differ from the eventual full scale drinking water production plant. Chemicals and energy use are extrapolated from other production schemes or estimates of manufacturers. The sensitivity of the analyses for these estimated data was carried out by setting minima and maxima for those variables and performing a sensitivity analysis. The membrane filtration variant is especially sensitive for the chosen recovery of the membrane filtration. Changing the source of primary energy used from the Dutch electricity mix to only wind electricity, does not change the fact that recovery is the most influential variable. However, the energy related to the variables ‘pressure for membrane filtration’, ‘energy for abstraction’ and ‘energy for oxygenation’ are replaced by the dosing of calcite and CO_2 for remineralization and the transport of calcite from France and Spain to the Netherlands. In other words, the next challenge to reduce the carbon footprint of the production process, after changing to a renewable energy source, is to purchase materials and chemicals from

suppliers that have comparable ambitions. It is also recommended to find sources as nearby as possible or reduce the impact of transport. Perhaps this is already the case. For most of these processes, generic data were used. Supplier specific data would improve the utility of this LCA as a hotspot analysis.

System boundaries
We assumed in this study that the distribution and use of the produced water would not change. However, the quality of the water that can be produced with membrane filtration is such that this system boundary could be challenged. For example, resulting reduction of scaling could increase the use phase of household equipment such as washing machines.

Other impacts
The results of this study can be used for a sustainability assessment that includes more considerations, like robustness (anticipation of fluctuating raw water quality in the future), investment costs and production costs, water use (membrane filtration uses more water), from waste to resource (conventional treatment produces side products, e.g. pellets).

Snapshot of development process
Because the drinking water production process is under development, this LCA is also under development. The model itself can be updated during the further development of the production process. Thus, the results presented in this background paper are a snapshot and will alter rapidly.

To be continued
The results trigger new research questions. The following will be further investigated:

- Can methane emissions be eliminated, e.g. with a helophyte filter?;
- Can CO_2 be withdrawn from the air on the production plant, instead of purchasing liquid CO_2?;
- Get in contact with suppliers to gain factual data on their production processes, to improve the LCA;
- Verification of the LCA results by monitoring the processes at a new comparable plant that uses membrane filtration (Lekkerkerk);
- Adding production costs to the model;
- Investigate if local solar energy would further improve the impact of energy use at the production plant.

Furthermore, various technical choices for the production process at Kamerik could now be investigated with the model, e.g. replace anti-scalant by calcium chloride and sodium hydroxide.

For now, this study provides a good first insight in the environmental performance of the two techniques and supports the further design of a sustainable production process.

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