A Comparative Life Cycle Assessment of Hybrid Osmotic Dilution Desalination and Established Seawater Desalination and Wastewater Reclamation Processes

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Supplementary Content for Material and Methods / Goal and Scope

The energy consumption and system design of unit processes for each scenario was either calculated from known principles of hydraulic flow or derived from manufacturer data, as summarized in Table S1 below.

Table S1. Sources of information for energy use estimates

Process	**Technology**	**Source of Data**
Intake Pumping	-	Hydraulic calculations
Pre-treatment	100 μm Disk Filter	Manufacturer data (Amiad)
	UF	Manufacturer data (Hydranautics)
Desalination	RO and NF	ROSA™ 6.1 (Dow-Chemicals 2009) (DOW, Filmtec)
	ODN	Custom software (Cath et al. 2009) with 80 psig boost prior to ODN
Energy recovery	PT™ Pressure Exchanger	ERI Power Model™ (ERI 2011)

Both seawater and wastewater are assumed to have a temperature of 20 °C. Systems were designed with an assumed TDS concentrations of 35,000 mg/L in the seawater and 850 mg/L in the wastewater (Wilf 2007, Tchobanoglous et al. 2003). Concentrations of chemical species are provided in Table S2 below.

Table S2. Concentration of principal electrolytes in seawater and wastewater effluent used in the ROSA™ software to design RO and NF unit processes.

	Concentration (mg/L)	
Constituent	**Seawater (Wilf 2007)**	**Wastewater Effluent (Tchobanoglous et al. 2003)**
Calcium	419	67
Magnesium	1,304	39.3
Potassium	390	107
Sodium	10,710	198
Bicarbonate	146	300
Chloride	19,350	238
Sulfate	2,690	309

Materials Used in Membrane Manufacturing

Materials used for the fabrication of membrane modules are another important component for the comparative LCA of the different water treatment scenarios. The types of materials used in UF, NF, and RO membrane modules are generally well known and consist of polyvinyl chloride (PVC) for the UF membrane housing and NF or RO central collection tube, low density polyethylene for the feed and permeate spacers of NF and RO membranes, fiberglass is used for NF and RO membranes wrapping, epoxy is frequently used to pot the ends of UF hollow fiber membranes and glue NF and RO membrane leafs, UF membranes are typically made from polyethersulfone or polypropylene, and NF and RO membranes are usually polyamide thin film composites (Baker, 2004; Mulder, 1997). The mass fraction of these different components in a membrane module is not reported in the literature, and in this study it was either measured in the laboratory or acquired from vendors for UF, RO, and NF membrane modules.

Membranes modules for FO and ODN do not share the same level of optimization in their packaging and materials as membranes used in established processes such as UF, NF, and RO. The mass of materials used to construct an industry-standard 4-inch spiral wound FO membrane (Hydration Technology Innovations, Albany, OR) was used as the baseline, and materials were scaled to simulate an 8-inch diameter membrane module with 6 membrane leafs using a corrugated feed spacer and draw solution spacers that are twice the thickness of RO permeate spacers. Materials used for the production of the FO membrane modules were similar to those used in the production of the RO membrane modules; the most significant exception being the use of cellulose triacetate (CTA) instead of polyamide for the FO membrane active layer.

The parameters described above were used to design the unit processes and estimate the consumables necessary to produce 1 m^3 of desalinated water. These values are compiled in the LCIs for each desalination and wastewater reclamation scenario.

Table S3. LCIs of Scenarios A, B, and C1. All values are presented on the basis of the functional unit and are reported per cubic meter of desalinated water produced. SimaPro product flow designation is shown in brackets where appropriate.

	Amount			Comments and SimaPro Designation
Scenario	***A***	***B***	***C1***	
INPUTS FROM NATURE				
Seawater, m^3	2.2	1.1	1.1	Resource extracted from the ocean
INPUTS FROM TECHNOSPHERE				
Wastewater, m^3	-	2.0	2.0	Secondary treated wastewater effluent
Electricity, kWh	2.5	1.9	1.9	Includes intake pumping, seawater and wastewater pretreatment, membrane treatment and CIP events
Scale inhibitor, kg ($x10^{-3}$)	4.0	6.9	13	Used for pressure driven desalination processes. [Sodium tripolyphosphate, at plant/RER S]
HCl, kg ($x10^{-4}$)	0.8	2.0	35	Disk filter and membrane cleaning chemical. [Hydrochloric acid, from Mannheim process, at plant/RER S]
H_2SO_4, kg ($x10^{-2}$)	0.8	1.4	40	UF cleaning chemical. [Sulphuric acid, liquid, at plant/RER S]
NaOH, kg ($x10^{-3}$)	2.0	3.6	1.0	Membrane cleaning chemical. [Sodium hydroxide, 50% in H_2O, production mix, at plant/RER S]
NaOCl, kg ($x10^{-3}$)	0.7	1.2	.35	Disk filter and UF cleaning chemical. [Sodium hypochlorite, 15% in H2O, at plant/RER S]
Na4EDTA, kg ($x10^{-2}$)	-	-	2.8	Cleaning reagent for ODN membrane. [EDTA, ethylenediaminetetraacetic acid, at plant/RER S]
SDBS, kg ($x10^{-4}$)	0.8	2.0	49	SWRO cleaning chemical. [Substitute used: Alkylbenzene sulfonate, linear, petrochemical, at plant/RER S]
$FeCl_3$, kg ($x10^{-3}$)	1.8	3.1	0.9	Pretreatment coagulant. [Iron (III) chloride, 40% in H_2O, at plant/CH S]
Epoxy, kg ($x10^{-4}$)	1.0	1.7	11	UF and RO membrane component. [Epoxy resin, liquid, at plant/RER S]
Fiber Glass, kg ($x10^{-4}$)	1.3	1.3	20	NF and RO membrane housing. [Glass fibre, at plant/RES S and Injection moulding/RER S]
Cellulose acetate, kg ($x10^{-3}$)	-	-	3.8	ODN membrane material. Substituted with: [Viscose fibres, at plant/GLO S and Extrusion, plastic film/RER S]
Polyamide, kg ($x10^{-4}$)	1.4	3.4	1.4	RO membrane material. [Polyamide 6.6 fibres (PA 6.6), from adipic acid and hexamethylene diamine (HMDA), prod. mix, EU-27 S and Extrusion, plastic film/RER S]
Polyethylene, kg ($x10^{-4}$)	1.9	4.7	6.5	NF and RO membrane flow channel spacer material. [Polyethylene, LDPE, granulate, at plant/RER S and Injection moulding/RER S]
Polypropylene, kg ($x10^{-4}$)	2.0	3.6	1.6	Disk filter and UF membrane. [Polypropylene, granulate, at plant/RER S and Injection moulding/RER S or Extrusion, plastic film/RER S as appropriate]
PVC, kg ($x10^{-4}$)	5.3	9.7	7.9	UF membrane housing or NF and RO central collection tube. [PVC injection moulding E]
OUTPUTS TO TECHNOSPHERE				
Potable water, m^3	1.0	1.0	1.0	Final water product prior to post treatment
CIP waste to sewer, kg	3.5	6.2	15.7	Discharge to sanitary sewer. [Wastewater Treatment plant, class3/CH/I S]
Discarded membrane materials, kg ($x10^{-3}$)	1.3	2.6	5.2	Landfill and incineration. [Waste scenario/CH S]
OUTPUTS TO NATURE				
Brine to ocean, m^3	1.0	0.5	1.0	Discharge to ocean
Wastewater to ocean, m^3	2.0	1.5	1.0	Discharge to ocean

Table S4. Impact categories of the CML 2001 method used to investigate various types of environmental impact associated with the treatment scenarios.

Impact Category	Units	Description of Method (Goedkoop et al. 1998)
Abiotic depletion potential (ADP)	kg Sb equivalent	ADP is determined for each extraction of minerals and fossil fuels as a mass of antimony equivalent.
Acidification potential (AP)	kg SO_2 equivalent	AP includes all emissions to air of acidifying substances that impact soil, groundwater, surface water, organisms, and infrastructure.
Eutrophication potential (EP)	kg PO_4 equivalent	EP includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water, and soil.
Fresh water aquatic ecotoxicity potential (FAETP)	kg 1,4-DB equivalent	FAETP includes all impacts on fresh water ecosystems, as a result of emissions of toxic substances to air, water, and soil. FAETP is based on a mass of 1,4-Dichlorobenzene equivalent.
Global warming potential (GWP) (100 years)	kg CO_2 equivalent	GWP includes emissions of greenhouse gasses to air as an indicator of the increase in radiative forcing (W/m^2) associated with climate change.
Human toxicity potential (HTP)	kg 1,4-DB equivalent	HTP includes all impacts of toxic substances on the human environment. Health risks of exposure in the working environment are not included. Ecotoxicity of a substance is based on a mass of 1,4-Dichlorobenzene equivalent.
Marine aquatic toxicity potential (MAETP)	kg 1,4-DB equivalent	MAETP includes impacts of toxic substances on marine ecosystems. Ecotoxicity of a substance is based on a mass of 1,4-Dichlorobenzene equivalent.
Ozone layer depletion potential (ODP)	kg CFC-11 equivalent	ODP includes the emissions of specific gases associated with the stratospheric ozone depletion. ODP of a substance is based on a mass of trichlorofluoromethane with an infinite time horizon.
Photochemical oxidation potential (POCP)	kg C_2H_4 equivalent	POCP includes the formation of reactive substances (mainly ozone) that are associated with poor air quality and have negative effects on human health and ecosystems and may also damage crops.
Terrestrial ecotoxicity potential (TETP)	kg 1,4-DB equivalent	TETP includes impacts of toxic substances on terrestrial ecosystems. Ecotoxicity of a substance is based on a mass of 1,4-Dichlorobenzene equivalent.

Supplementary Content for Results and Discussions / Baseline Comparative LCIA of Water Treatment Scenarios

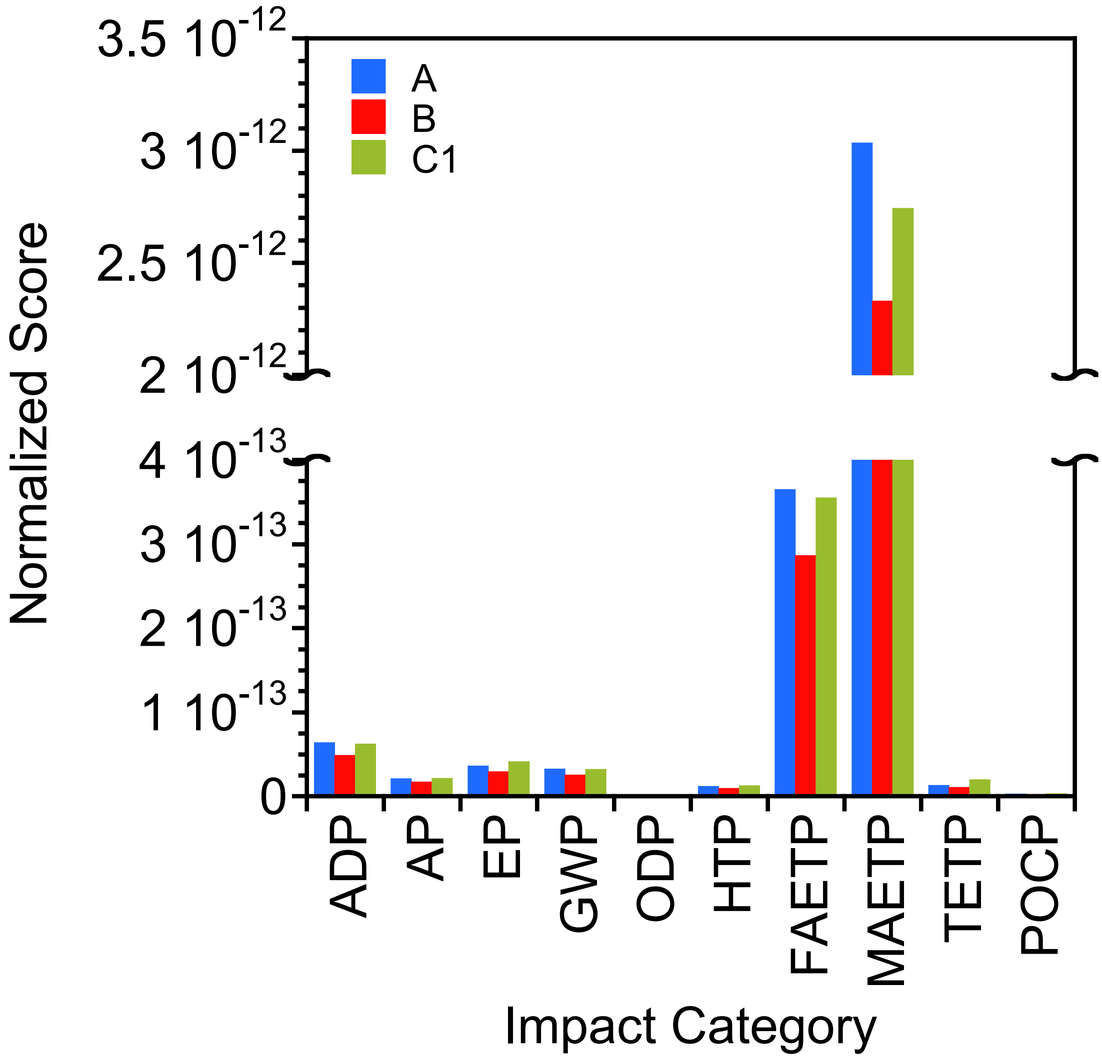

Figure S1. Normalized score of Scenarios A, B, and C1 evaluated using data for the World in 1995 based on the CML 2 baseline 2000, V2.05. Scenario C1 is for the ODN membrane with the baseline membrane A_{w0} value (0.36 L/m^2·h·bar).

Supplementary Content for Results and Discussions / FO Membrane Optimization

Example for Calculation of Power Density in ODN

A second observation is that the power density of the ODN may be calculated by multiplying the specific energy savings (kWh/m^3) of the SWRO process due to seawater feed dilution by the nominal water flux through the FO membrane used in the ODN process. The following equation is used in calculating the equivalent energy density of the ODN process combined with SWRO:

$$\boldsymbol{P_{ODN} = \left(\left(E_{BaselineRO} - E_{ERD}\right) - \left(E_{ROw/ODN} - E_{ERDw/ODN}\right)\right) \times J_{ODN}}$$

where P_{ODN} is the power density of the ODN process (W/m^2), $E_{BaselineRO}$ is the specific energy per m^3 water produced for baseline seawater salinity (kWh/m^3) estimated with ROSA (Dow-Chemicals 2009), E_{ERD} is the estimated energy recovered per m^3 water produced, estimated with the ERI model (kWh/m^3) (ERI 2011), $E_{ROw/ODN}$ is the specific energy per m3 water produced for SWRO case with diluted water under same flow conditions to the RO membrane ($E_{BaselineRO}$) (kWh/m^3), $E_{ERDw/ODN}$ is the estimated energy recovered per m^3 water produced for the SWRO desalinating ODN-diluted seawater, and J_{ODN} is the nominal flux of water through the ODN membrane in m^3/m^2-hr.

As an example, we have simulated an ODN system for treatment of 2 million gallons per day (MGD) (7,571 m^3/day) to produce 1 MGD (3,785 m^3/day) of product water. The RO system is simulated to operate at 50% water recovery. Calculations were conducted with the currently available FO membranes having permeability of 1.08 L/m^2·h·bar (A_{w3}) operated at 61% water recovery from the impaired water. Under this case, $E_{BaselineRO}$ = 3.98 kWh/m^3, E_{ERD} = 2.41 kWh/m^3, $E_{ROw/ODN}$ = 1.78 kWh/m^3 kWh/m^3, $E_{ERDw/ODN}$ = 1.33 kWh/m^3, and J_{ODN} = 0.0102 m^3/m^2-hr. Using the equation above, P_{ODN} = 0.0114 kW/m^2 = 11.4 W/m^2.

Supplementary Content for Results and Discussions / New Comparative LCIAs of Water Treatment Scenarios

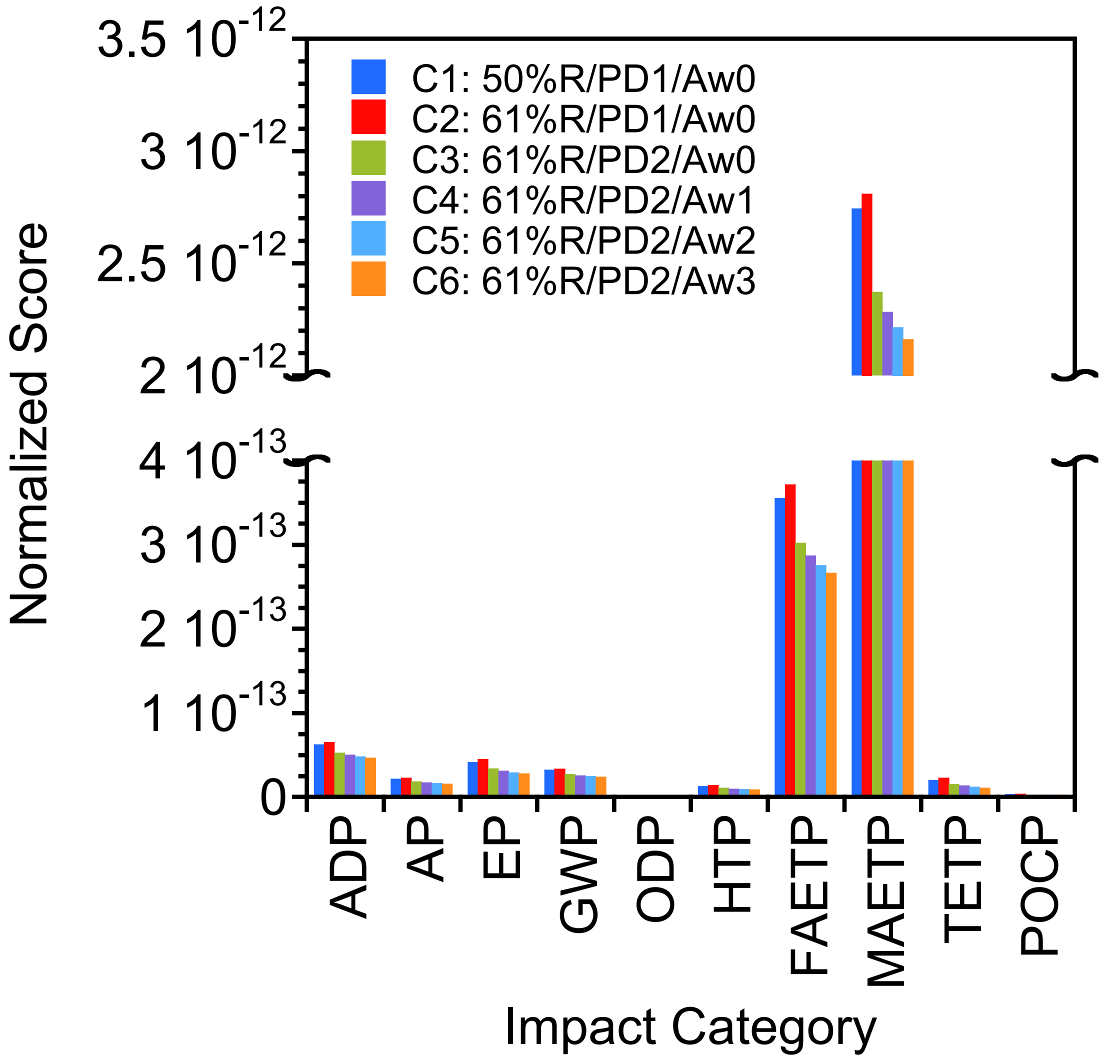

Figure S2. Normalized score of various improvements to the ODN membrane and module in Scenario C, evaluated using data for the World in 1995 based on the CML 2 baseline 2000, V2.05. %R represent percent ODN water recovery, PD1 represent packing density of 9.5 m^2/module, PD2 represent 20 m^2/module, and Aw represent the different FO membrane permeance coefficients.

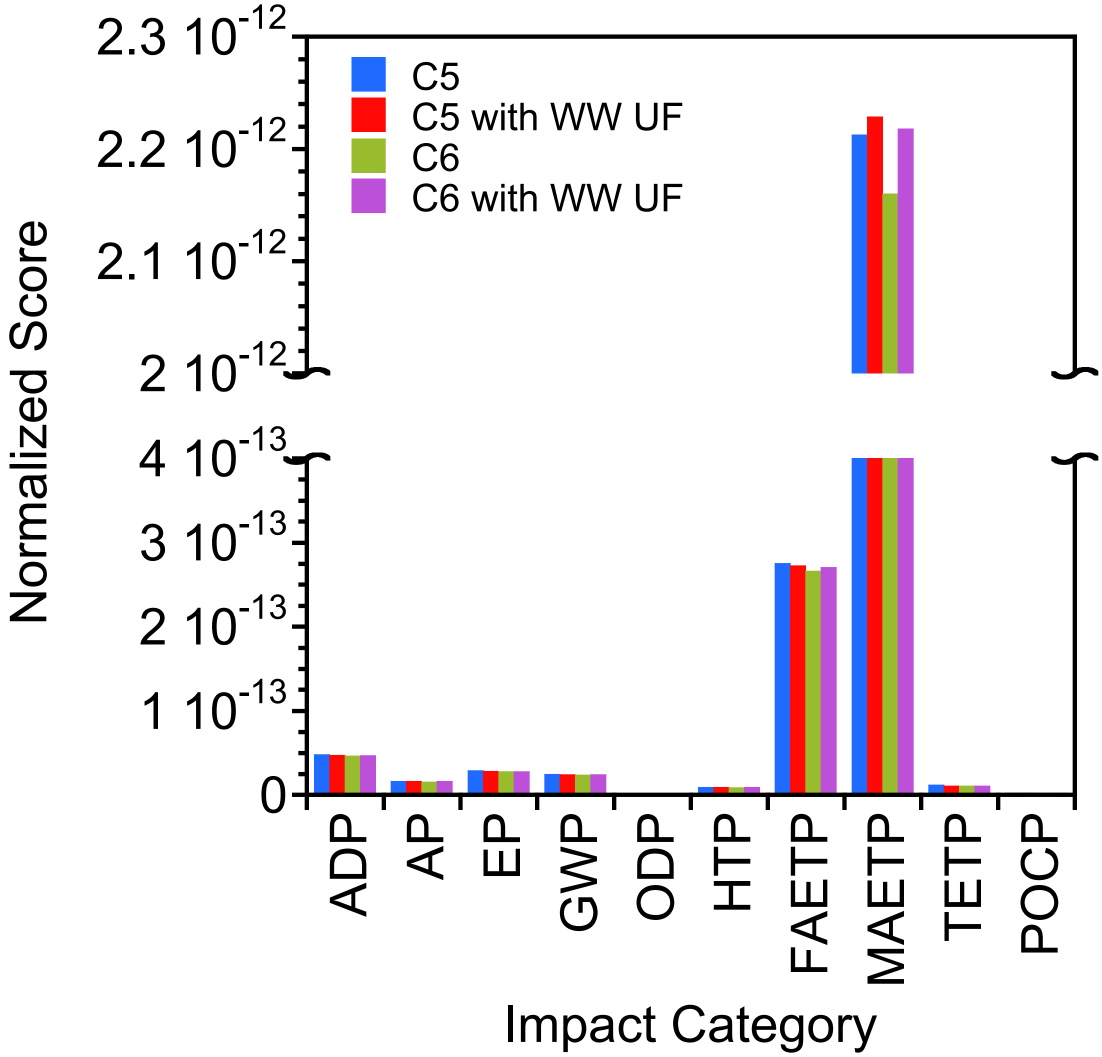

Figure S3. Normalized score of UF pretreatment of the ODN feed stream prior to the FO membranes across the ten impact categories of Scenarios C5 and C6 evaluated using data for the World in 1995 based on the CML 2 baseline 2000, V2.05. In all cases the ODN water recovery is 61% and the membrane packing density is 20 m^2/module.

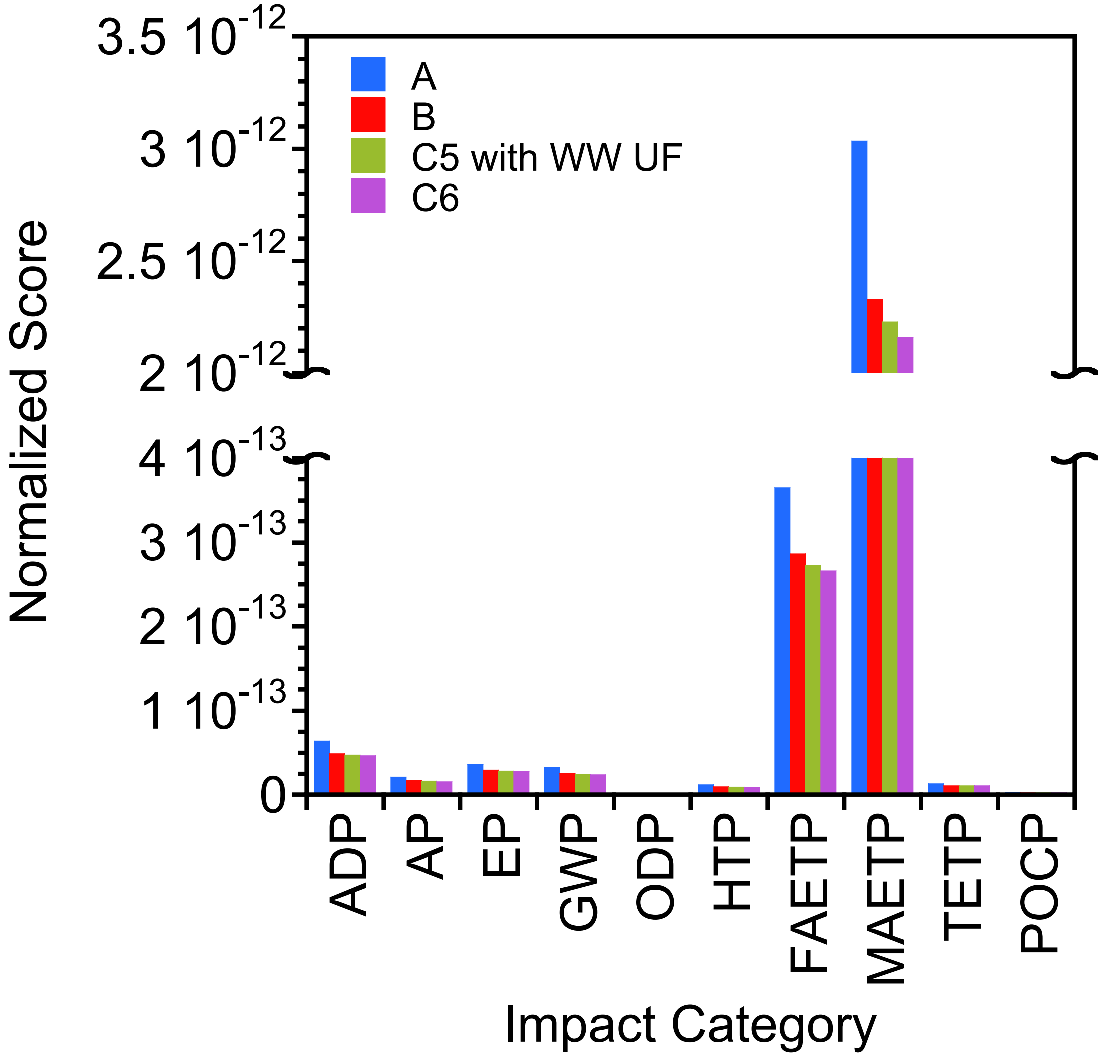

Figure S4. Normalized score for Scenarios A, B, C5 with UF pretreatment of ODN feed, and C6. Impact categories were evaluated using data for the World in 1995 based on the CML 2 baseline 2000, V2.05. Legend descriptors are provided in the captions of Figure S2 and S3.

References

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