

Supplementary Materials

Functional and environmental performances of novel electrolytic membranes for PEM fuel cells: a lab-scale case study

Section S1. Goal and Scope

Table S1. Experimental data of Nafion® 212, SGO, GONS, and BSGO. Proton conductivity values refer to the EIS tests performed on rectangular samples exposed to T=80 °C and RH=100%.

Membrane	Experimental mass (g/DU)	Experimental thickness (μm)	Experimental conductivity (S cm ⁻¹)
Nafion® 212	1.628	50.8	0.56
SGO	1.364	12.0	1.15
GONS	0.803	17.1	1.71
BSGO	1.397	11.6	0.19

Section S2. Life Cycle Inventory (LCI) of the involved materials

Table S2.1. LCI of the production of Graphene Oxide (GO) [48].

INPUTS			
Flow	Provider	Amount	Unit
Graphite	Market for graphite, battery grade – GLO	0.71	kg
Sulfuric acid (H ₂ SO _{4,aq})	Market for sulfuric acid – RER	30.20	kg
Deionized water	Market for water, ultrapure – RER	223	kg
Hydrogen peroxide (H ₂ O ₂ , 100%)	Market for hydrogen peroxide, w/o water, 50% solution state – RER	1.24	kg
Sodium nitrate (NaNO ₃)	Market for sodium nitrate – GLO	0.36	kg
Potassium permanganate (KMnO ₄)	Market for potassium permanganate – GLO	2.14	kg
Calcium hydroxide (Ca(OH) ₂)	Market for lime, hydrated, loose weight – RoW	22.80	kg
Electricity	Market group for electricity, medium voltage – EU w/o CH	10	MJ
OUTPUTS			
Flow	Provider	Amount	Unit
Graphene Oxide (GO)	GO, for laboratory	1.00	kg

Table S2.2. LCI of the production of Nafion® [49].

INPUTS			
Flow	Provider	Amount	Unit
Tetrafluoroethylene (C ₂ F ₄)	Market for tetrafluoroethylene – GLO	1.30	kg
Sulfur trioxide (SO ₃)	Market for sulfur trioxide – RER	0.50	kg
Hexafluoropropene (C ₃ F ₆)	Market for hexafluoropropene – GLO	3.20	kg
Sodium hypochlorite (NaClO)	Market for sodium hypochlorite, w/o water, 15% solution state – GLO	3.00	kg
Sodium hydroxide (NaOH)	Market for sodium hydroxide, w/o water, 50% solution state – GLO	0.60	kg
Sodium carbonate (Na ₂ CO ₃)	Market for soda ash, dense – GLO	0.11	kg
Organics	Market for chemical factory, organics – GLO	4.00 × 10 ⁻¹⁰	Items

Process heat	Market group for heat, district or industrial, and natural gas – RER	39.31	MJ
Transport lorry	Market group for transport, freight, lorry, unspecified – GLO	0.87	t·km
Transport train	Market for transport, freight train – EU w/o CH	5.22	t·km
OUTPUTS			
Flow	Provider	Amount	Unit
Nafion® membrane	Nafion membrane®, for PEMFC	1.00	kg
Sodium chloride (NaCl)	Sodium chloride, to water	2.36	kg
Sodium hydroxide (NaOH _{aq})	Sodium hydroxide, to water	1.87	kg
Sodium fluoride (NaF)	Sodium fluoride	8.48×10^{-2}	kg
Carbon dioxide (CO ₂)	Carbon dioxide, fossil, to air	8.88×10^{-2}	kg
Organic residue	Treatment of spent solvent mixture – EU w/o CH	2.81	kg
Plastic residue	Treatment of waste plastic, mixture – EU w/o CH	0.11	kg
Oily residue	Treatment of bilge oil – EU w/o CH	0.38	kg

Table S2.3. LCI of the production of a Sulfonated Graphene Oxide (SGO) membrane.

INPUTS			
Flow	Provider	Amount	Unit
Graphene Oxide (GO)	GO, for laboratory	0.60	g
Sulfuric acid (H ₂ SO _{4,aq})	Market for sulfuric acid – RER	15.90	g
Deionized water	Market for deionized water – EU w/o CH	600	g
Electricity	Market group for electricity, medium voltage – EU w/o CH	32.87	MJ
OUTPUTS			
Flow	Provider	Amount	Unit
Sulfonate Graphene Oxide (SGO)	SGO membrane, for PEMFC	1.364	g
Wastewater	Treatment of wastewater – EU w/o CH	600	g

Table S2.4. LCI of the production of a Graphene Oxide-Naphthalene Sulfonate (GONS) membrane.

INPUTS			
Flow	Provider	Amount	Unit
Graphene Oxide (GO)	GO, for laboratory	0.60	g
Naphthalene sulfonic acid (NS)	Market for naphthalene sulfonic acid – GLO	0.783	g
Deionized water	Market for deionized water – EU w/o CH	300	g
Electricity	Market group for electricity, medium voltage – EU w/o CH	124.96	MJ
OUTPUTS			
Flow	Provider	Amount	Unit
Graphene Oxide-Naphthalene Sulfonate (GONS)	GONS membrane, for PEMFC	0.803	g
Wastewater	Treatment of wastewater – EU w/o CH	300	g

Table S2.5. LCI of the production of a Borate-reinforced Sulfonated Graphene Oxide (BSGO) membrane.

INPUTS			
Flow	Provider	Amount	Unit
Graphene Oxide (GO)	GO, for laboratory	0.60	g
Sulfuric acid (H ₂ SO _{4,aq})	Market for sulfuric acid – RER	15.90	g
Sodium tetraborate decahydrate (Na ₂ B ₄ O ₇ ·10H ₂ O)	Market for Borax, anhydrous, powder – GLO	0.081	g
Deionized water	Market for deionized water – EU w/o CH	600	g
Electricity	Market group for electricity, medium voltage – EU w/o CH	39.64	MJ
OUTPUTS			
Flow	Provider	Amount	Unit
Borate-reinforced Sulfonated Graphene Oxide (BSGO)	BSGO membrane, for PEMFC	0.803	g
Wastewater	Treatment of wastewater – EU w/o CH	600	g

Section S3. Supplementary results of Life Cycle Impact Assessment

EF 3.0 method [65] is the impact assessment method adopted in Environmental Footprint transition phase of the European Commission and it includes normalization [66] and weighting factors [67].

Table S3.1. Impact assessment results of Nafion® 212, SGO, GONS, and BSGO per DU at the normalization step.

Impact category	Unit	Nafion® 212	SGO	GONS	BSGO
Climate change	–	4.49×10^{-5}	4.49×10^{-4}	1.70×10^{-3}	5.39×10^{-4}
Ozone depletion	–	1.39×10^{-4}	3.34×10^{-6}	1.26×10^{-5}	4.01×10^{-6}
Ionizing radiation	–	2.67×10^{-6}	4.92×10^{-4}	1.87×10^{-3}	5.93×10^{-4}
Photochemical ozone formation	–	8.04×10^{-6}	1.98×10^{-4}	7.45×10^{-4}	2.37×10^{-4}
Particulate matter	–	8.32×10^{-6}	1.00×10^{-4}	3.67×10^{-4}	1.18×10^{-4}
Human toxicity, non-cancer	–	2.13×10^{-5}	1.47×10^{-4}	5.51×10^{-4}	1.76×10^{-4}
Human toxicity, cancer	–	2.06×10^{-5}	6.10×10^{-5}	2.28×10^{-4}	7.30×10^{-5}
Acidification	–	1.19×10^{-5}	3.55×10^{-4}	1.32×10^{-3}	4.23×10^{-4}
Eutrophication, freshwater	–	2.50×10^{-5}	2.24×10^{-3}	8.48×10^{-3}	2.69×10^{-3}
Eutrophication, marine	–	4.67×10^{-6}	1.72×10^{-4}	6.50×10^{-4}	2.07×10^{-4}
Eutrophication, terrestrial	–	5.25×10^{-6}	1.66×10^{-4}	6.26×10^{-4}	2.00×10^{-4}
Ecotoxicity, freshwater	–	9.73×10^{-5}	9.86×10^{-4}	3.56×10^{-3}	1.17×10^{-3}
Land use	–	3.79×10^{-7}	1.37×10^{-5}	5.17×10^{-5}	1.64×10^{-5}
Water use	–	5.61×10^{-6}	7.76×10^{-5}	2.82×10^{-4}	9.14×10^{-5}
Resource use, fossils	–	1.92×10^{-5}	1.18×10^{-3}	4.46×10^{-3}	1.41×10^{-3}
Resource use, minerals and metals	–	4.67×10^{-5}	1.37×10^{-4}	5.05×10^{-4}	1.62×10^{-4}

Table S3.2. Impact assessment results of Nafion® 212, SGO, GONS, and BSGO per DU after weighting, scores are in milli-ecopoints (mPt).

Impact category	Unit	Nafion® 212	SGO	GONS	BSGO
Total	mPt	2.96×10^{-2}	3.72×10^{-1}	1.40×10^0	4.47×10^{-1}
Climate change	mPt	9.47×10^{-3}	9.45×10^{-2}	3.57×10^{-1}	1.13×10^{-1}
Ozone depletion	mPt	8.77×10^{-3}	2.11×10^{-4}	7.95×10^{-4}	2.53×10^{-4}
Ionizing radiation	mPt	1.34×10^{-4}	2.47×10^{-2}	9.36×10^{-2}	2.97×10^{-2}
Photochemical ozone formation	mPt	3.84×10^{-4}	9.44×10^{-3}	3.56×10^{-2}	1.13×10^{-2}
Particulate matter	mPt	7.45×10^{-4}	9.00×10^{-3}	3.29×10^{-2}	1.06×10^{-2}
Human toxicity, non-cancer	mPt	3.92×10^{-4}	2.70×10^{-3}	1.01×10^{-2}	3.23×10^{-3}
Human toxicity, cancer	mPt	4.38×10^{-4}	1.30×10^{-3}	4.85×10^{-3}	1.55×10^{-3}
Acidification	mPt	7.36×10^{-4}	2.20×10^{-2}	8.21×10^{-2}	2.62×10^{-2}
Eutrophication, freshwater	mPt	7.01×10^{-4}	6.26×10^{-2}	2.37×10^{-1}	7.54×10^{-2}
Eutrophication, marine	mPt	1.38×10^{-4}	5.10×10^{-3}	1.92×10^{-2}	6.13×10^{-3}
Eutrophication, terrestrial	mPt	1.95×10^{-4}	6.14×10^{-3}	2.32×10^{-2}	7.38×10^{-3}
Ecotoxicity, freshwater	mPt	1.87×10^{-3}	1.89×10^{-2}	6.83×10^{-2}	2.25×10^{-2}
Land use	mPt	3.01×10^{-5}	1.09×10^{-3}	4.10×10^{-3}	1.30×10^{-3}
Water use	mPt	4.77×10^{-4}	6.60×10^{-3}	2.40×10^{-2}	7.78×10^{-3}
Resource use, fossils	mPt	1.59×10^{-3}	9.78×10^{-2}	3.71×10^{-1}	1.18×10^{-1}
Resource use, minerals and metals	mPt	3.53×10^{-3}	1.03×10^{-2}	3.81×10^{-2}	1.22×10^{-2}

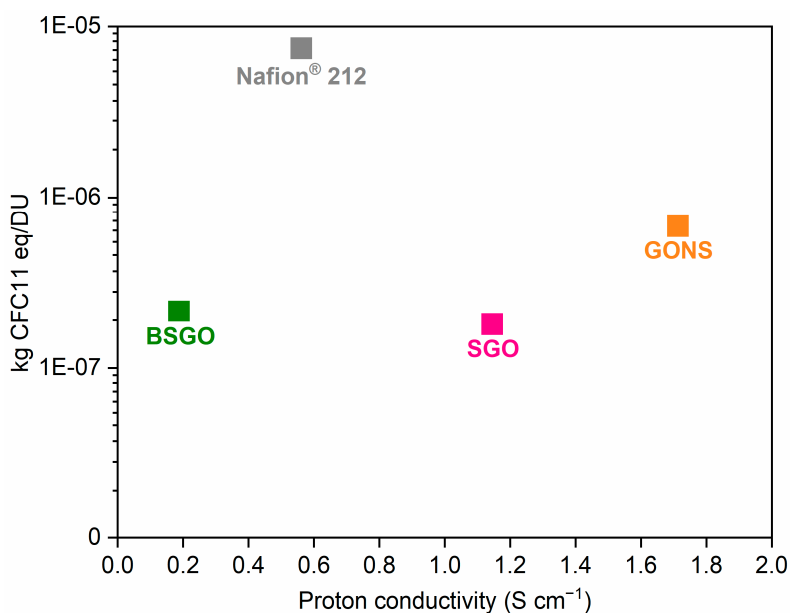


Figure S3.1. Ozone depletion of Nafion® 212, SGO, GONS, and BSGO with respect to their corresponding proton conductivity.