Recent innovations and future advances of alternatives to PFAS in lithium-ion batteries (and other green energy technologies)

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Eleni Savvidou
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Jon Benskin
Steffen Schellenberger
Xianfeng Hu
Marcel Weil
and others…

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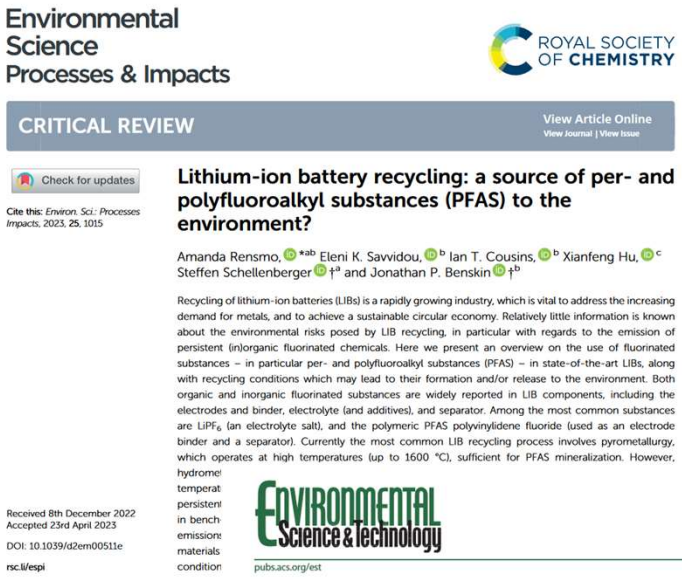
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Lithium-ion battery recycling: a source of per- and polyfluoroalkyl substances (PFAS) to the environment?

Amanda Rensmo, Eleni K. Savvidou, Ian T. Cousins, Xianfeng Hu, Steffen Schellenberger and Jonathan P. Benskin

Recycling of lithium-ion batteries (LIBs) is a rapidly growing industry, which is vital to address the increasing demand for metals, and to achieve a sustainable circular economy. Relatively little information is known about the environmental risks posed by LIB recycling, in particular with regards to the emission of persistent (in)organic fluorinated chemicals. Here we present an overview on the use of fluorinated substances – in particular per- and polyfluoroalkyl substances (PFAS) – in state-of-the-art LIBs, along with recycling conditions which may lead to their formation and/or release to the environment. Both organic and inorganic fluorinated substances are widely reported in LIB components, including the electrodes and binder, electrolyte (and additives), and separator. Among the most common substances are $LiPF_6$ (an electrolyte salt), and the polymeric PFAS polyvinylidene fluoride (used as an electrode binder and a separator). Currently the most common LIB recycling process involves pyrometallurgy, which operates at high temperatures (up to 1600 °C), sufficient for PFAS mineralization. However, hydrome
temperat
persisten
in bench
emission
materials
condition

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Perspective

PFAS-Free Energy Storage: Investigating Alternatives for Lithium-Ion Batteries

Eleni K. Savvidou,* Amanda Rensmo, Jonathan P. Benskin, Steffen Schellenberger, Xianfeng Hu, Marcel Weil, and Ian T. Cousins*

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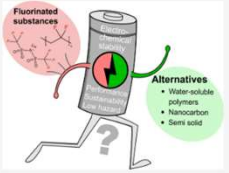


ABSTRACT: The class-wide restriction proposal on perfluoroalkyl and polyfluoroalkyl substances (PFAS) in the European Union is expected to affect a wide range of commercial sectors, including the lithium-ion battery (LIB) industry, where both polymeric and low molecular weight PFAS are used. The PFAS restriction dossiers currently state that there is weak evidence for viable alternatives to the use of PFAS in LIBs. In this Perspective, we summarize both the peer-reviewed literature and expert opinions from academia and industry to verify the legitimacy of the claims surrounding the lack of alternatives. Our assessment is limited to the electrodes and electrolyte, which account for the most critical uses of PFAS in LIB cells. Companies that already offer or are developing PFAS-free electrode and electrolyte materials were identified. There are also indications that PFAS-free electrolytes are in development by at least one other company, but there is no information regarding the alternative chemistries being proposed. Our review suggests that it is technically feasible to make PFAS-free batteries for battery applications, but PFAS-free solutions are not currently well-established on the market. Successful substitution of PFAS will require an appropriate balance among battery performance, the environmental effects associated with hazardous materials and chemicals, and economic considerations.

KEYWORDS: *fluoropolymers, PVDF, renewable energy, green energy transition, cathode, binder, electrolyte salt, electrolyte additives*

Are PFAS essential in green energy technologies (GETs)? Should *we* allow the use of PFAS in GETs?

- Not a yes/no question
  - Look closer (components)
  - Look broader (sub-uses)
- Today, there are commercially available alternatives to PFAS (technology and/or material)
- Full alternatives assessments are necessary to avoid regrettable substitution

Background: Fluoropolymers are included in the definition of PFAS

"PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS."

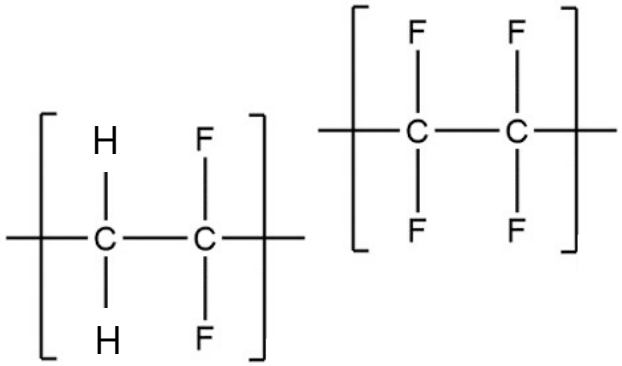
"All PFASs are considered to be very persistent, either on the basis of their own very persistent properties or the very persistent properties of their terminal degradation product (arrowhead) Additional hazardous properties depend on the specific structure of a PFAS."

OECD (2021)
ECHA (2023)

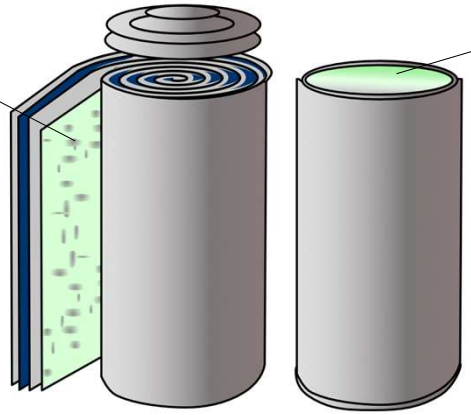
Case 1: PFAS are used in lithium-ion batteries as binder and electrolyte, e.g. PVDF and TFSI

Cathode

Binders
Fluoropolymers



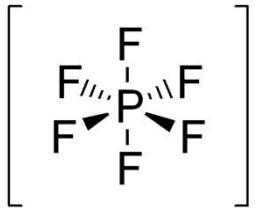
PVDF - polyvinylidene fluoride



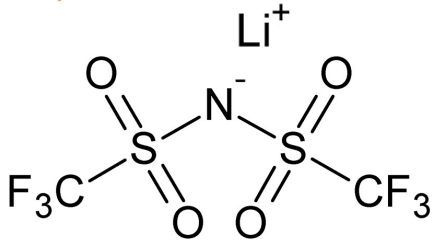
Electrolyte

Liquid electrolytes
Lithium-salts

Li^+



(not a PFAS)



TFSI - bis(trifluoromethanesulfonyl)imide

Rensmo et al (2023)
Savvidou et al. (2024)

"The inclusion of **fluorine-based compounds** in the electrolyte chemistry is, to date, ubiquitous as a pathway to promote the targeted formation of lithium fluoride, known to be a favourable SEI component in lithium batteries."

"By increasing the **perfluoroalkyl chains** in the sulfonimide anions, efficient stabilization of cathode-electrolyte interface could be also achieved.[189]"

189. Tong B et al. (2023) Design of a Teflon-like Anion for Unprecedently Enhanced Lithium Metal Polymer Batteries *Adv. Energy Mater.* **13** 2204085

"Presently, the dry PE-based SSBs, consisting of a thin membrane of **LiTFSI**/PEO, metallic lithium (Li°) anode, and LiFePO4 cathode, have been employed as power source for EVs (e.g. Bluecars®, Bluebuses®) and grid storage (e.g. Bluestorage®)."

"…with increasing concerns on the use of polyfluoroalkyl substances (PFASs; being harmful to human and animals), excluding long **perfluorinated chains from polymers and salts** would be important for attaining sustainable technology with PE-based SSBs."

JPhys Energy

ROADMAP • OPEN ACCESS

2024 roadmap for sustainable batteries

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… and also in "future" battery technologies

Case 1: There are various alternatives on the market to PVDF and TFSI

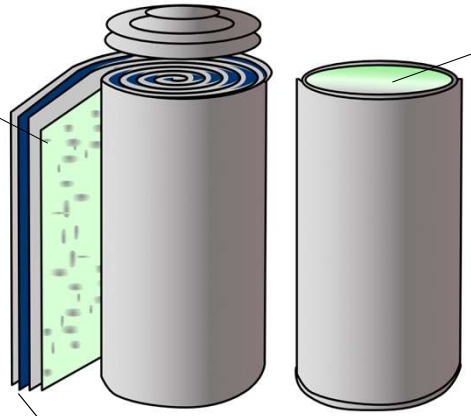
*lists not exhaustive

Cathode

Water-soluble binders
Biobased polymers

Solvent-free binders
Nanocarbon

Binder-free technologies



Electrolyte

Liquid electrolytes
E.g. borates
See more in Hernández et al. (2022)

Polymer electrolytes
Poly(ethylene oxide)

Solid/Metal batteries
PFAS-free ionic liquids
See more in Liu et al. (2025)

Anode

Styrene-Butadiene Rubber (SBR)
Carboxymethylcellulose (CMC)
Polyacrylic acid (PAA)

Savvidou et al. (2024)

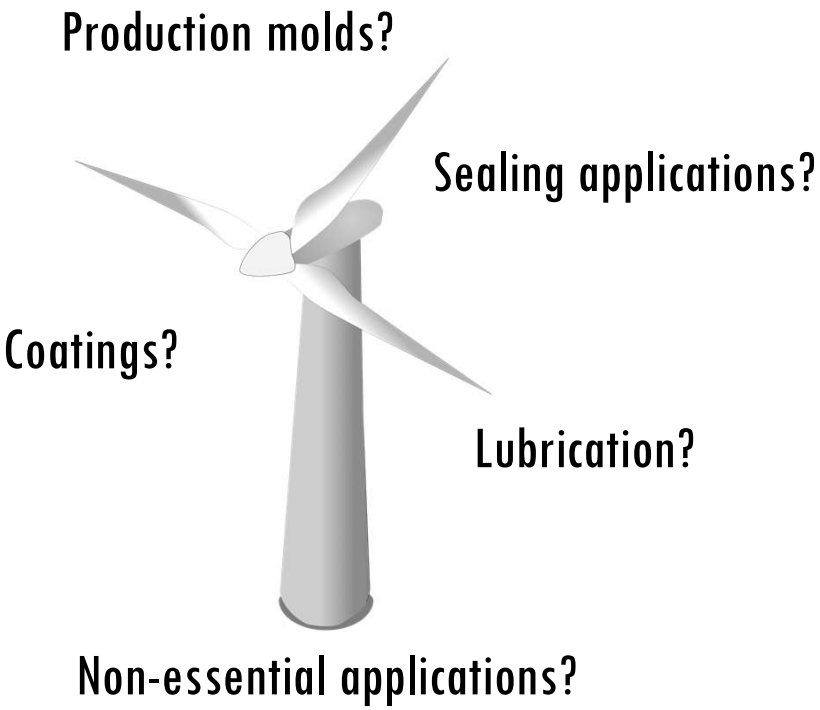
Case 2: The chemical industry, parts suppliers and wind energy sceptics claim that PFAS is used in wind energy

"In particular, fluoropolymers are key materials for the majority of the strategic technologies assessed including Li-ion batteries, fuel cells, wind turbines, solar photovoltaics"

"In the field of wind turbines, fluoropolymers are used as coatings on the towers and blades of wind power generators…"

"…ticking PFAS bomb under the wind turbines that stand out at sea…" (translated)

"County Opposes Lake Erie Wind Turbines:
/…/Some of the concerns the resolution noted included:/…/
– Release of microplastics and toxic chemicals, such as BPA and PFAS, from wind turbine materials"

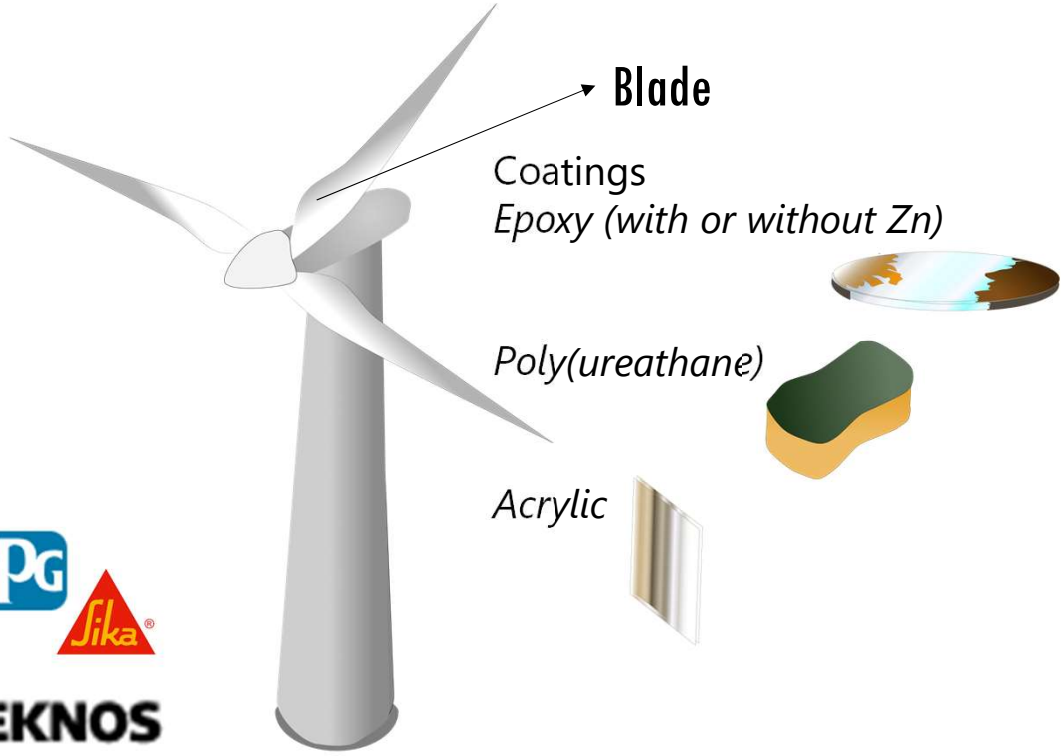


ECHA submissions: FPG Fluoropolymers Product Group (ref_6148), 3P Performance Plastics Products (ref_6275); Media: Ingeniøren (Danish), The Post-Journal

Case 2: Commercial wind turbines do not contain PFAS in the main components such as the blade

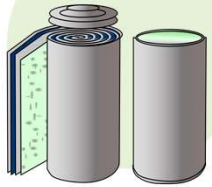
"The wind industry is already using PFAS-free coatings for the rotor blades. And it continuously assesses whether other components and materials may contain PFAS and, if so, whether PFAS-free alternatives are available."

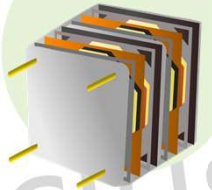
Wind EUROPE

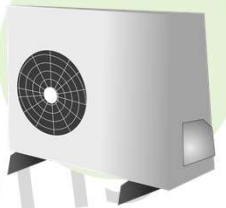


B. Kjærside Storm (2013)
A. Dashtkar et al. (2019)

What about major GETs – do they use PFAS or not? If so, are there alternatives on the market?







Solar panels (Si)	Wind turbines	Batteries (Li-NMC)	Fuel cells (PEM)	Heat pumps
PFAS in supporting components	No PFAS in main components	PFAS in main component(s)	PFAS in main component	PFAS in main component
Market alternatives available	"Alternatives" implemented	Alternative sub-uses without PFAS in main component(s)	Alternative sub-uses without PFAS in main component	Alternatives available, historically used

See more in Glüge et al. (2024)

Are PFAS essential in green energy technologies (GETs)? Should *we* allow the use of PFAS in GETs?

- All five major GETs have PFAS-free alternatives (technology and/or material) with various TRL
- Some functions are shared among several GETs
- My work: Look closer and broader
  - use of PFAS in both main and supporting components of GETs
  - uses of PFAS for different sub-uses of GETs

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"There are a number of scientific approaches we can take to make a safer and more sustainable environment, whilst still improving the usability of energy storage [including] remov[ing] chemicals that can potentially produce such toxic materials as PFAS during recycling"

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Beyond the Nobel recognition – To a cleaner sustainable future

M. Stanley Whittingham

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