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Lithium-Sulfur batteries
- Developing next generation battery technology platform

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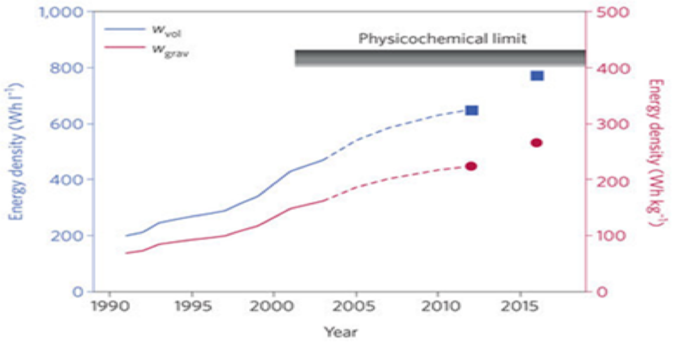
Conventional Lithium-Ion NMC battery technology has some clear limitations

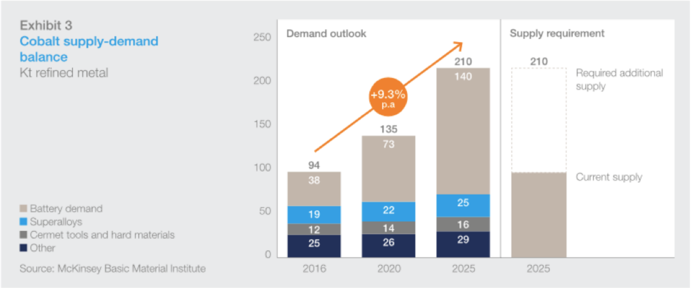
Insufficient gravimetric energy density/ capacity

- Practical limit:
  300 – 350 Wh/kg
- Poor depth of discharge means limits full capacity utilisation (>



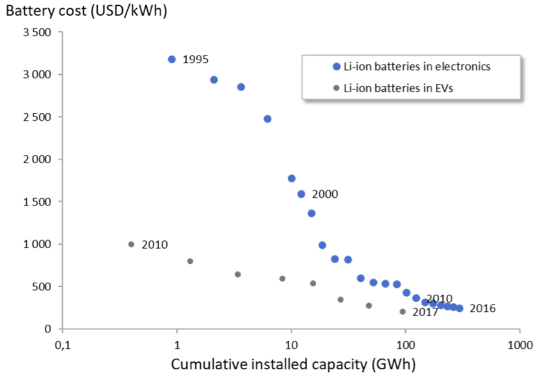
Availability of Cobalt

- Key assumptions:
  - Low Cobalt technology (NMC 811) dominant
  - Only 30% of new cars are electric vehicles
- Still Cobalt is predicted to be a scarce material



Cost

- Further significant cost reductions challenging (cost pr kWh)
- Cyclical pricing of rawmaterials
- Energy intensive in processing and manufacturing
- Expensive to recycle



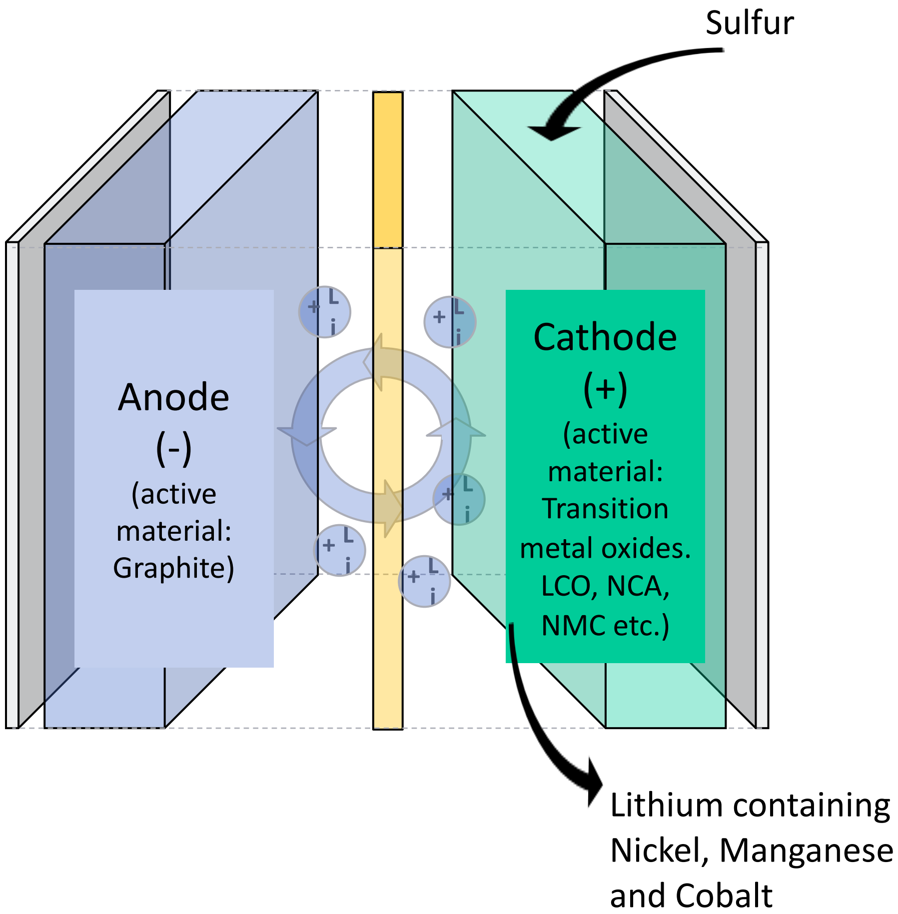
Environmental and ethical challenges

- Uses conflict metals such as Cobalt
- Using hazardous chemicals in manufacturing (NMP)
- Significant CO2 emissions in processing and manfucturing
- Very difficult to recycle

To accelerate the energy transition there is a need to develop a new technology platform for batteries

Why is Lithium-Sulfur the next generation technology platform for batteries

The core basic concept of Lithium Sulfur technology



Lithium Sulfur technology (vs conventional Li-Ion technology) …

… can store 2-3X more specific energy (theoretically 5-6X)

- 700 Wh/kg vs 300 Wh/kg

… will cost significantly less (<100 USD/ kWh)

- Price of raw material price in NMC vs Sulfur is 500:1 and significantly less energy intensive in mining, processing and manufacturing

… do not need conflict materials and are manufactured much more environmental friendly

- No Cobalt, Nickel nor Manganese needed, less energy intensive processing and no hazardous chemicals

… maintain performance at very low temperatures and do not need to remain charged

- Remain liquid down to -60C

… are less explosive and flammable and also less sensitive to shock and pressure

Department of Energy in the US sees Lithium Sulfur as the next generation technology platform for Lithium-Ion batteries

Steven Chu, former US Secretary of Energy and Nobel price winner in physics, has identified Li Sulfur as the next generation batteries

Steven Chu

Chu has mentioned before that he and Yi Cui of Stanford's Materials Science Department are working on a next-generation battery that could improve energy density five times and charging rate up to ten times over conventional lithium-ion batteries. The new battery would be made from lithium and sulfur.

Department of Energy in the US view Li Sulfur as a key technology to break the 500 Wh/kg barrier

Battery500 initiative

Home > News > Battery Tech

DoE Selects 15 Recipients For Seed Money To Work Towards Battery With Specific Energy Of 500 Wh/kg

AUG 27, 2017 at 4:00PM

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Lithium Sulfur as a key technology

"The Battery500 project is focused on three keystone projects:

- A high nickel content cathode with a Li-metal anode;
- Sulfur cathode and Li-metal anode; and
- Innovative electrode and cell design."

In the Battery500 consortium, Li Sulfur is the key technology and the only two car companies (GM and Mercedes) both target Li Sulfur

Battery500 seeding projects – Phase 1 awards

University of Maryland: College Park - $400,000

Research innovative iron-based materials for high energy cathodes for high energy lithium ion battery technologies.

Lawrence Berkeley National Laboratory - $400,000 Research thick cathodes using freeze casting methods for solid-state lithium batteries.

Penn State University Park - $399,194 Research multifunctional Li-ion conducting interfacial materials that enable high- performance lithium metal anodes.

Mercedes-Benz Research & Development North America, Inc. - $400,000 Research a scalable synthesis to enable very thin coatings on solid state electrolyte membranes to enable high performance Li-Sulfur Battery.

University of Maryland: College Park - $400,000 Using 3D printed, low tortuosity frameworks, develop solid state Li-ion batteries.

General Motors LLC - $400,000 Design, engineer, develop, and integrate pouch-format cells for lithium-sulfur batteries to achieve high energy density and long cycle life.

University of Pittsburgh - $400,000 Research sulfur electrodes utilizing lithium ion conductor (LIC) coatings for high energy density advanced lithium-sulfur (Li-S) batteries.

Cornell University - $360,000 Research highly loaded sulfur cathodes and conductive carbon coated separators that enable high energy batteries.

University of Maryland: College Park - $400,000 Research advanced electrolytes to limit dendrite growth in lithium-metal cells.

Texas A&M Engineering Experiment Station - $400,000 Utilize an analytical and experimental approach to examine the interface between solid state electrolytes and lithium-metal anodes and identify potential methods for mitigating dendrite growth.

Navitas Advanced Solutions Group, LLC - $400,000 Research a solvent-free process to fabricate all-solid Li batteries.

Wayne State University - $225,000 Research novel full-cell, ultra high-energy Li- metal batteries based on 3-dimensional architectures.

Oregon State University - $353,500 Research and develop a new process to produce Li2S@graphene composite cathodes to inhibit polysulfides to enhance cycle life.

SUNY University at Stony Brook - $400,000 Research li-sulfur batteries using a novel sulfur rich nanosheet composite cathode.

University of Houston - $400,000

Research high-energy solid-state lithium batteries with organic cathode materials.

The only two car-companies both focus on Li Sulfur technology

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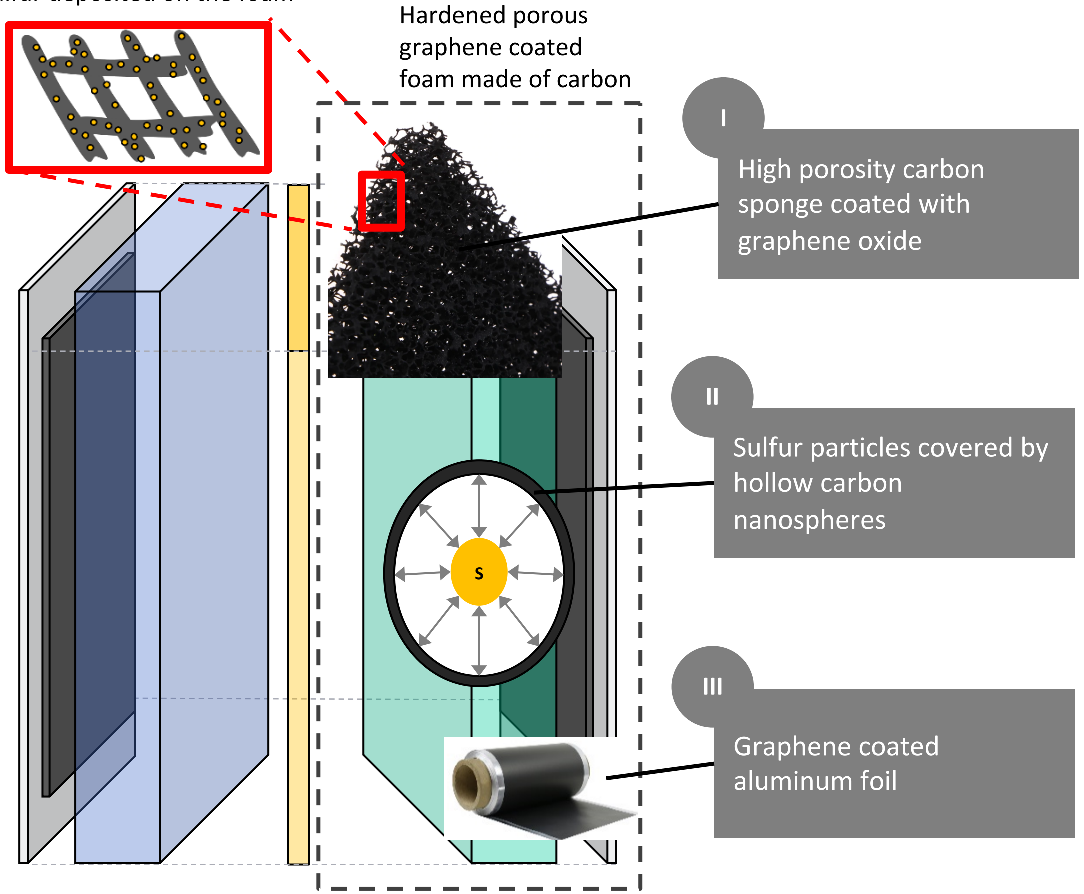
BEBA/GB has solved the key challenges of developing a high performing Lithium-Sulfur battery

Key challenges of Lithium-Sulfur

1. Sulfur expands volume by 80% when discharged
2. Sulfur is non-conductive
3. Loss of active Sulfur in discharge
4. Achieve high active material loading
5. Dendrite formation in the anode

BEBA's solution(s)



Cathode

1) Can also be used in the anode side. Next step to apply same technology on the anode side where Lithium metal is infiltrated instead of Sulfur

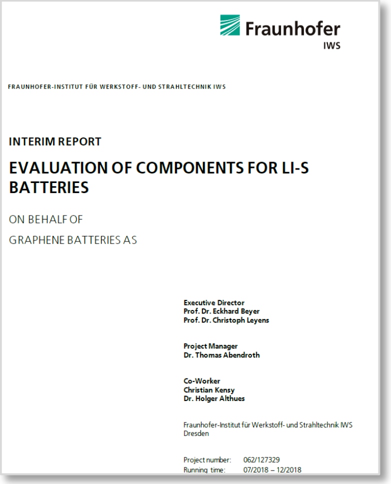
The breakthroughs have been verified by two tests conducted by the leading battery research institute in Europe; Fraunhofer Batterien

Fraunhofer BATTERIEN

Excerpts from evaluation papers of Graphene Batteries' technology:

- "address one of the most pressing bottlenecks of Li-S battery"
- "outstanding pouch cell results in terms of gravimetric energy and cycle life expected"
- "significant progress towards high performance for high energy Li-S batteries"

Test 1:



Fraunhofer IWS

FRAUNHOFER-INSTITUT FÜR WERKSTOFF- UND STRAHLTECHNIK IWS

INTERIM REPORT

EVALUATION OF COMPONENTS FOR LI-S BATTERIES

ON BEHALF OF

GRAPHENE BATTERIES AS

Executive Director
Prof. Dr. Eckhard Beyer
Prof. Dr. Christoph Leyens

Project Manager
Dr. Thomas Abendroth

Co-Worker
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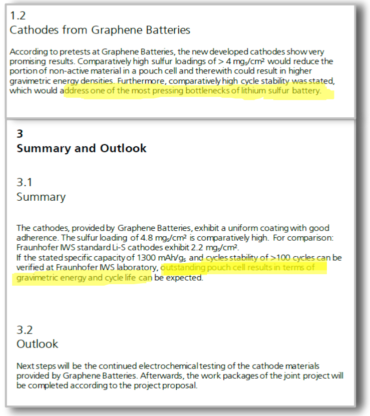
Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS
Dresden

Project number: 062/127329
Running time: 07/2018 – 12/2018



1.2
Cathodes from Graphene Batteries

According to pretests at Graphene Batteries, the new developed cathodes show very promising results. Comparatively high sulfur loadings of > 4 mg_s/cm^2 would reduce the portion of non-active material in a pouch cell and therewith could result in higher gravimetric energy densities. Furthermore, comparatively high cycle stability was stated, which would address one of the most pressing bottlenecks of lithium sulfur battery.

3
Summary and Outlook

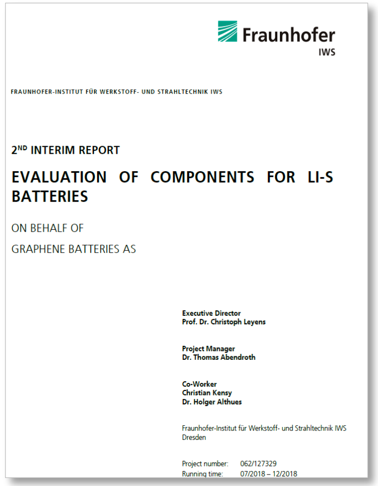
3.1
Summary

The cathodes, provided by Graphene Batteries, exhibit a uniform coating with good adherence. The sulfur loading of 4.8 mg_s/cm^2 is comparatively high. For comparison: Fraunhofer IWS standard Li-S cathodes exhibit 2.2 mg_s/cm^2.
If the stated specific capacity of 1300 mAh/g_s and cycles stability of >100 cycles can be verified at Fraunhofer IWS laboratory, outstanding pouch cell results in terms of gravimetric energy and cycle life can be expected.

3.2
Outlook

Next steps will be the continued electrochemical testing of the cathode materials provided by Graphene Batteries. Afterwards, the work packages of the joint project will be completed according to the project proposal.

Test 2:



Fraunhofer IWS

FRAUNHOFER-INSTITUT FÜR WERKSTOFF- UND STRAHLTECHNIK IWS

2ND INTERIM REPORT

EVALUATION OF COMPONENTS FOR LI-S BATTERIES

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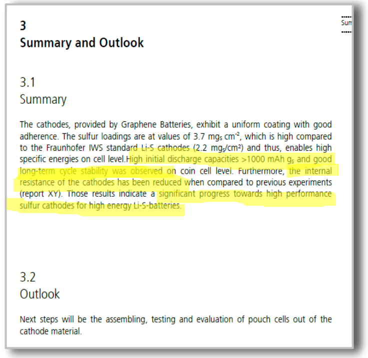


3
Summary and Outlook

3.1
Summary

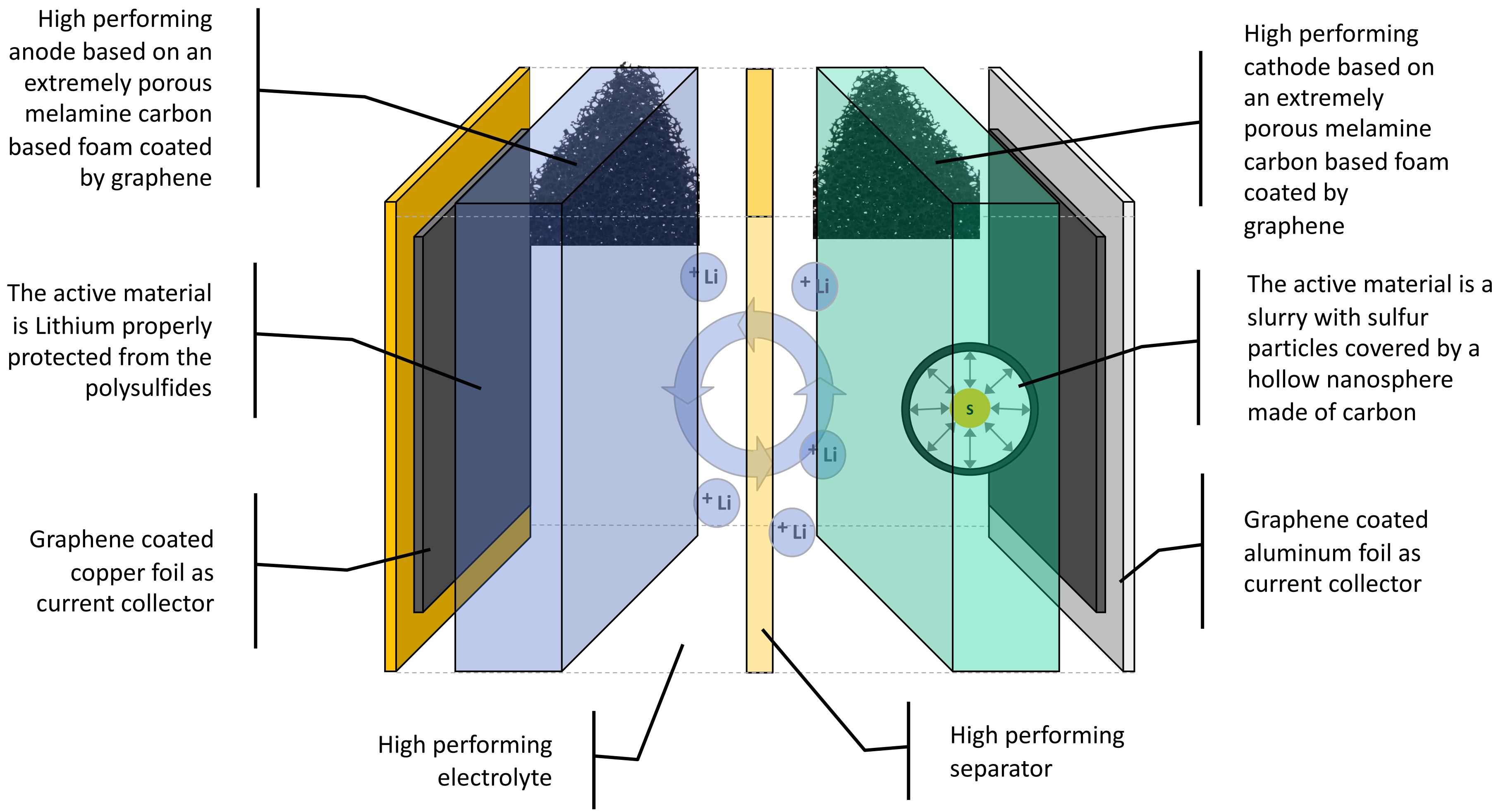
The cathodes, provided by Graphene Batteries, exhibit a uniform coating with good adherence. The sulfur loadings are at values of 3.7 $mg_S\ cm^{-2}$, which is high compared to the Fraunhofer IWS standard Li-S cathodes (2.2 mg_S/cm^2) and thus, enables high specific energies on cell level. High initial discharge capacities >1000 $mAh\ g_S$ and good long-term cycle stability was observed on coin cell level. Furthermore, the internal resistance of the cathodes has been reduced when compared to previous experiments (report XY). Those results indicate a significant progress towards high performance sulfur cathodes for high energy Li-S-batteries.

3.2
Outlook

Next steps will be the assembling, testing and evaluation of pouch cells out of the cathode material.

Fraunhofer confirms not only that the technology works – but that the results are state of the art for Li-S batteries

BEBA aims to start pilot manufacturing Lithium-Sulfur battery cells in 2 years



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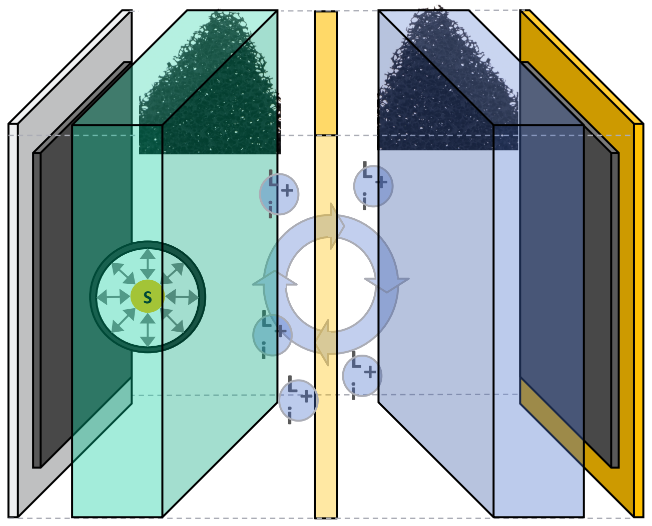
The technologies can both be used to manufacture a fully functioning Li-S battery and/or as components to both existing Li-ion or the emerging Li-S industry

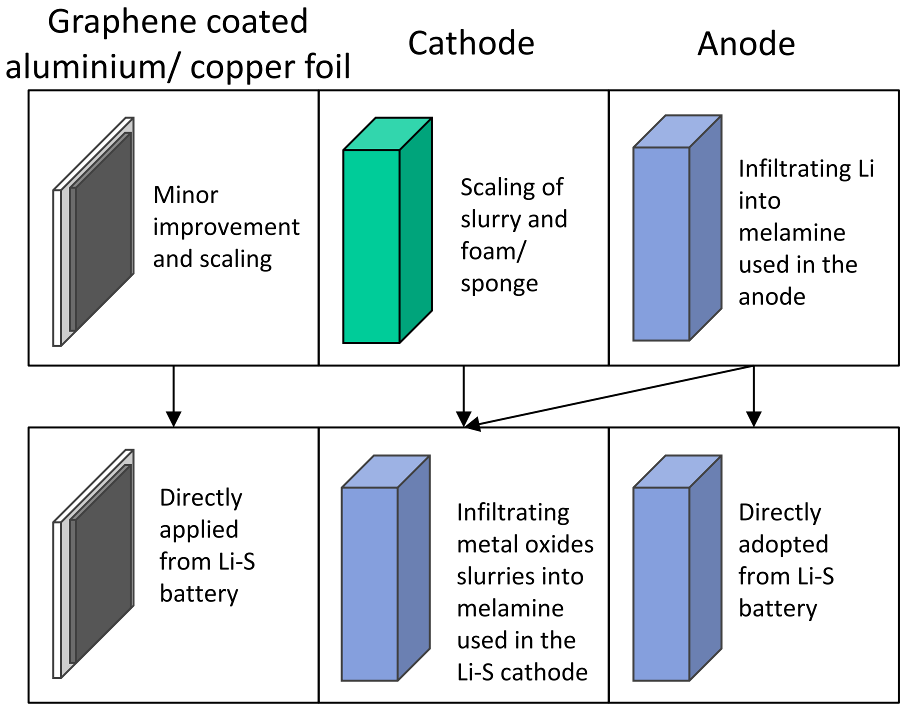
A fully functioning Li-S battery cell



Set of state-of-the-art technologies for both the existing Li Ion and the developing Li-S industry

Technology developed for the Li-S Industry …

… can also be applied for Li-Ion Industry



Potential customers from the existing Li-ion industry: Panasonic SAMSUNG SDI LG Chem

Establishing an ecosystem of partners with complementary capabilities and resources are critical for BEBA's success

Innlandet Battery Initiative

NTNU BELLONA SINTEF Eidsiva

Market potential significant – even in niche segments

*"Market demand for energy storage is **"limitless"***
*if **cost** is sufficiently low and **energy density** is sufficiently high."*

Elon Musk

Lithium-Sulfur battery is particularly well suited for applications where weight, energy density and cost is critical and volume is less critical

These are the battery markets of the future!

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