Department of

BATTERY TECHNOLOGY

IFE Institute for Energy Technology

2023

OUR MISSION

is to build a secure battery materials and technology value chain for Norway and our partners. To accomplish this, we are establishing the country's most advanced laboratories for battery materials validation and cell testing, operated by a team of scientists and engineers with depth and range of competence unique to our institute.

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A MESSAGE

This is an exciting time to be a battery researcher in Norway. We can see momentum and progress across the entire battery ecosystem from basic materials research to cell production. The whole field is buzzing with activity and optimism for the future.

At IFE our research supports industrial partners with state-of-the art scientific and engineering competence and the most advanced laboratories in the country for battery characterization and testing. We also work with academia and other research institutes on cutting edge research. The Battery Technology Department at IFE is now one of Norway's largest research groups on batteries, and we continue to grow to meet the rising activity level in the field. We maintain a close dialogue with our partners and have a good overview of future technologies and innovations to further increase our relevance in industrial, applied and basic research.

2023 will see an exciting expansion of our battery labs, with a state-of-the-art pilot line for pouch cells, dry rooms and new testing facilities. This will allow us to study materials at larger scale with maximum flexibility to meet the requests of our partners. The 500 m^2 of new lab space represents one of the largest recent investments at IFE. The pilot line will be part of the Norwegian Advanced Battery Laboratory (NABLA) national infrastructure, supported by the Research Council of Norway.

Batteries are an essential part of the global green transition, meaning that the production and use of batteries will continue to increase dramatically over the coming years. To meet this demand in a sustainable way requires the development of a new battery value chain based on low environmental impact. The development of technology based on abundant and environmentally benign materials is essential as is the use of green energy in production. Functional and scalable recycling processes and routes for the re-use of batteries need to be developed. At IFE we relish the opportunity to meet these challenges in battery research.

from: Hanne Flåten Andersen,
head of Battery Technology Department

ORGANIZATION

WHO ARE WE?

The Department of Battery Technology was officially established on January 1st 2018. It is led by Dr Hanne Flåten Andersen and comprises researchers and engineers with the depth and range of competence required to perform service and research work. As part of the Energy Materials (ENMAT) section of IFE we work closely with colleagues in solar cell research and materials process modelling.

WHAT DO WE WORK ON?

Our research efforts are centered around development of battery materials; fabrication and testing of battery cells and modules; and analysis of the lifetime and degradation of new and used commercial batteries. We work with partners from every stage of the value chain to support the development and deployment of new and emerging battery technologies in Norway, Europe and beyond.

WE AIM TO:

- Build Norway's biggest and best qualified team of scientists and engineers fully focused on battery research.
- Establish Norway's most advanced laboratories for battery materials validation and cell testing.
- Build and maintain relevance as a research partner for all sectors of the battery ecosystem in Norway and beyond.
- Create an interactive organization of scientists conducting experiments, theory and numerical modelling in concert.

Department coordinator
Monica Christina Økland

Business developer
Sigmund Sørensen Kielland

Research director (ENMAT)
Arve Holt

BATTERY DEPT.

BATTERY TECHNOLOGY

Group leader:
Jan Petter Mæhlen

Head:
Hanne Flåten Andersen

Group leader:
Samson Yuxiu Lai

MATERIALS DEVELOPMENT

Scientists Engineers

Muhammad Abdelhamid, Carl Erik Lie Foss, Abirdu Woreka Nemaga, Marte Orderud Skare, Alexey Koposov, Raphael Kuhn, Marius Uv Nagell, Marta Koposova, Theresa Nguyen, Zbigniew Rozynek, Asbjørn Ulvestad, Tommy Vikan Nordby, Preben Joakim Svela Vie, Julia Wind, Volodymyr Yartis, David Wragg, John Ostrander, Jonathan Fagerström

PEOPLE

The Battery Technology Department has 23 staff members with experience from leading battery technology, materials, physics and chemistry research groups around the world. Many of the team members have worked in the field for more than 10 years and have a deep knowledge of the history and state of the art in battery research and technology, as well as informed perspectives on future developments. As well as providing research services and conducting cutting-edge research, we focus strongly on training. We supervise and host PhD students working on collaborative projects with academic and industrial partners, train young scientists, and provide continuous development opportunities for our research staff to expand their skillsets both scientifically and as managers of large projects and facilities.

Our recently employed business development manager helps the team to build and maintain relationships with key industrial partners and funding agencies, aiming to ensure the best possible strategic and financial outcomes for the department. He is also heavily engaged in research proposal writing and creating consortia for applications to European and national funding programs.

37% Senior researchers

29% Young researchers

21% Engineers

13% Technical and administrative staff

GEOGRAPHICAL ORIGINS OF OUR EMPLOYEES

50% Norway

13% USA

9% Poland

4% Ethiopia

4% UK

4% Austria

4% Germany

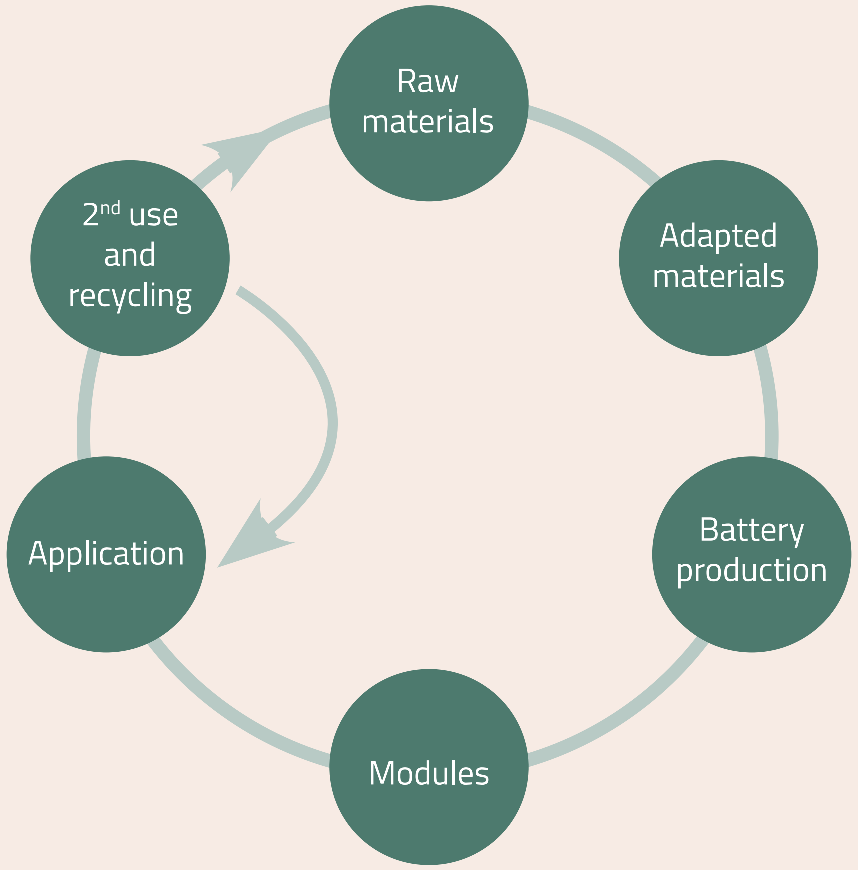
4% Egypt

4% Ukraine

4% Finland

Our research team is highly international and includes members with experience and education from leading European research groups and collaborations around the world. Because of this the Department presents our customers with a wide range of experience and knowledge and connects them to an extensive network of top battery researchers beyond IFE.

BATTERY VALUE CHAIN



Management consultants McKinsey & Company forecast that the market for battery cells will grow, on average, by more than 20 percent per year until 2030, reaching a total value of at least USD360 billion globally. The biggest opportunities exist in Europe and North America, which have relatively immature markets and where, unlike China or South Korea, the battery value chain is not fully established.

Over a number of years, the Norwegian government has supported growth in the battery industry with direct financial incentives. It now also plays an important role in encouraging and financing the development of local battery ecosystems.

The lithium-ion battery value chain comprises six main segments: (1) mining and processing of raw materials; (2) cell component manufacturing; (3) cell manufacturing; (4) assembly of cells into packs and modules including electronic management; (5) integration of modules and packs into products and their use; and (6) battery reuse and/or recycling.

At IFE we possess significant expertise in segments 1–3, 6 and are expanding our team to increase the knowledge on module assembly and battery management systems. We work with partners covering the entire value chain in Norway and across Europe to support the development and deployment of new and emerging battery technologies.

Improving European and national self-sufficiency, energy efficiency, and sustainability, requires creation of a circular battery economy. At the Battery Technology Department we also investigate opportunities for "second-life" uses of batteries when they are no longer suitable for their initial purpose, and study how to efficiently harvest minerals from them once they no longer fulfill that second purpose.

LABORATORIES

Battery **Materials** Laboratory

In the Battery Materials Laboratory we produce battery materials by chemical vapour deposition. We use both fluidized bed and free-space reactors to produce micro- or nanosized particles and can tailor the composition, size,morphology and crystallinity of the products. The materials are produced by decomposition of gases (e.g., silane), and an additional focus of the lab is understanding and optimizing the chemistry and reactor engineering used in these processes. In addition, we focus on post-processing of the produced materials where we develop coatings, morphology optimization and hybdridization techniques.

Battery **Development** Laboratory

The Battery Development Laboratory houses a collection of equipment for converting materials into working batteries for testing and characterization. Electrolyte materials are mixed into slurries which can be characterised with rheometry to find the optimal composition with binders and additives. Slurries are coated onto current collectors using a doctor blade or slot die and assessed for thickness and roughness. The electrodes are then assembled into coin or pouch cells in the glove boxes. We have particular experience in working with silicon anodes and lithium ion batteries, which is highly transferable to other battery types.

Battery **Testing** and **Characterization** Laboratory

IFE is the leading institution in Norway for testing and characterization of batteries. We offer an extensive equipment portfolio and decades of experience in the field. The cells are stored and cycled in controlled temperature chambers, including fire proof facilities for larger cells. Accelerated testing and advanced lifetime models are available. The laboratory offers electrochemical testing, galvanostatic cycling, electrochemical impedance spectroscopy, emulation of drive-cycles, constant current, power, voltage and resistance cycling, characterization of degradation, and many more tests.

MATERIALS DEVELOPMENT

Born from the infrastructure investments of the Norwegian solar industry, the Battery Materials Laboratory aims to synthesize and develop advanced materials for the next-generation of electrochemical energy storage solutions, including Li-ion and Na-ion batteries.

IFE's unique on-site experimental facilities can produce silicon-based active materials through thermal pyrolysis of silane and other reactive gases.

Using a variety of reactors, we can synthesize and study a wide range of materials, from the scale of molecules to kilograms, with combinations of properties not available commercially, such as amorphous nanoparticles with chemical alloying. We can then further functionalize these materials with coatings through thermal or dry-impact hybridization processes. These tools are also used to develop our bio-derived carbon-based materials for Na-ion batteries.

All in all, the advantage of our Battery Materials Laboratory is vertically integrating more of the battery value chain in one department, allowing iterative materials design in collaboration with the Battery Development Laboratory, and accelerating the deployment of new technology to commercial markets.

Samson Yuxiu Lai
(Ph.D), **Group Leader**
is a materials science and characterization expert, previously working on in situ synchrotron studies of solid oxide fuel cells before coming to IFE to study silicon nanoparticles with neutron scattering. His current focus is on reducing the dependency on critical raw materials for Li-ion batteries and capacitors and enhancing performance through surface modification.

STUDY EXAMPLE

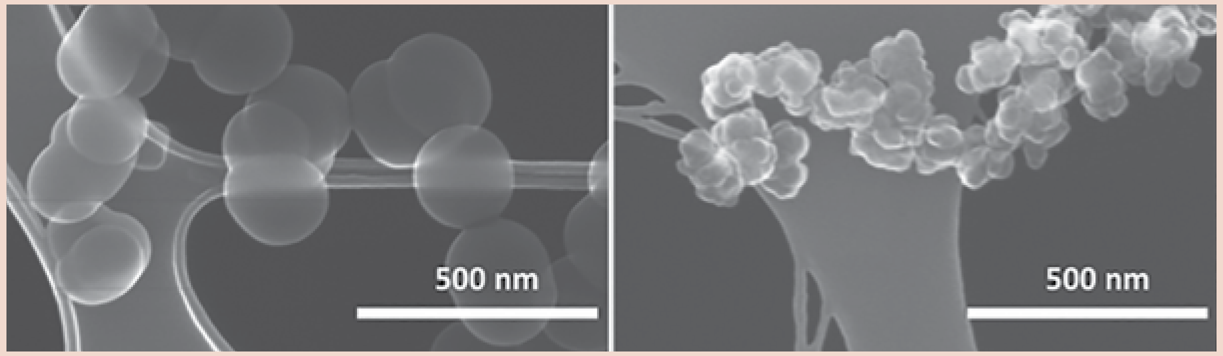


Fig. 1. Scanning electron microscopy images of two types of amorphous Si nanoparticles produced from silane pyrolysis.

We have developed a new silicon-based material, amorphous substoichiometric silicon nitride (SiNx), aiming to solve the challenges of increasing the lifetime and capacity of the anodes of Li-ion batteries. IFE has published both papers and patents on SiNx, and is investing together with Kjeller Innovasjon through the FORNY2020 commercialization project SiliconX to upscale the technology. SiNx shows very much less capacity loss during charge and discharge when compared with pure silicon particles, which have much higher capacity but much shorter lifetimes than the graphite used in anodes today.

Fig. 2.
SiliconX material, produced at IFE, can be the answer to longer lasting, higher capacity lithium-ion batteries.

Fig. 3. Due to the presence of many uniquely hazardous gases and high temperatures, health and safety for both our researchers and the environment are a top priority for IFE.

The Battery Materials Laboratory comprises:

- Customized free space reactor for the production of silicon and silicone-based nanoparticles from thermal pyrolysis of silane and other reactive gases
- Fluidized bed reactor (FBR) for larger-scale production of silicon active materials using silane, reactive gases, and microparticle Si seeds
- Gas distribution and safety infrastructure for handling of hazardous reactive gases (silane, phosphine, ammonia, acetylene, hydrogen, etc.)
- Scrubber plant for safe handling of exhaust gases and waste particles
- Gas analysis equipment with mass spectrometry (MS) and gas chromatography mass spectroscopy (GC-MS) specialized for silane and silane derivatives
- Real-time, remote visual monitoring of exhaust and particle detection from the reactor control room
- Carbon coating and compositing using thermal reduction ovens, dry-impact particle hybridizer, and other particle processing equipment

PARTICLE PRODUCTION

Built for safety and reliability, the FornyLab is a synthesis sandbox for materials development. It consists of a tailored infrastructure for handling hazardous gases, such as gas distribution, reactor controls, gas analysis, exhaust management and a gas detection and monitoring system. Combined with an isolated control room, this infrastructure enables the operation of the two main silane pyrolysis reactors, the free space reactor (FSR) and the fluidized bed reactor (FBR).

These reactors have been re-purposed in the battery revolution to produce amorphous Si nanoparticles. Silane gas (SiH_4) is heated through a flowing tube, which spontaneously polymerizes into disilane, trisilane, etc. until it nucleates into nanoparticles, which are then harvested using a system of filters. By introducing other gases like ammonia or phosphine, the nanoparticles' chemical composition can be altered to include nitrogen or phosphorus, and their electrochemical properties modified to achieve new, highly performing battery materials.

Tommy Vikan Nordby
(B. Eng.), **Engineer**
is a precision mechanic and mechanical engineer with experience in manufacture and mechanical design as well as gas instrumentation and infrastructure. His current work consists of optimizing, running and maintaining reactors, infrastructure and equipment in the materials development laboratory.

Free space reactor **(FSR)**

The FSR is the experimental testbed for developing new materials and chemistries while being optimized to produce particles of a consistent size, morphology, and size distribution. Built using custom-engineered parts informed by fluid flow simulations, the FSR injects a mix of precursor gases into a precisely heated reactor chamber, inducing near-homogeneous nucleation conditions to produce nanoparticles in sufficient quantities for lab-scale experiments (up to 150 g per batch). It is a highly flexible, modular reacto, which is customized for different projects and IFE engineers are constantly developing new ways to expand its capabilities.

Fluidized bed reactor **(FBR)**

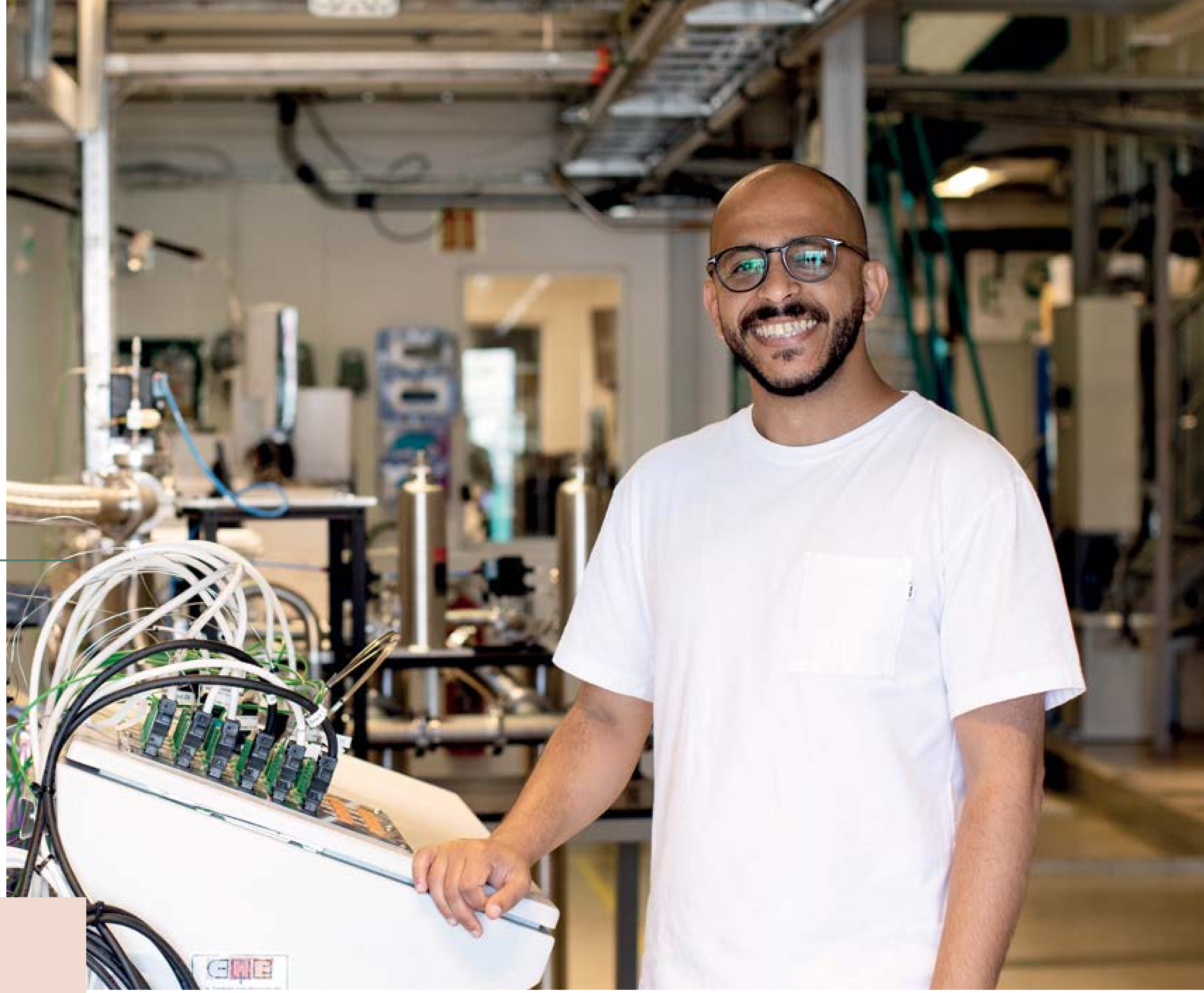
When larger quantities of silicon materials are needed, we turn to our fluidized bed reactor. This reactor can make the same compositions of materials as our FSR, but is both larger in size and has a much more efficient mechanism of heat transfer. This allows it to utilize a lot more precursor gas thus producing more material.

The FBR uses a well-developed commercial technology in which a bed of micron-sized seed particles is fluidized with sufficiently high gas flow. The seeds can effectively control the reaction rate and create a more uniform heat distribution through the flowing gas, or even serve as the growth surface for new materials. This leads to a combination of chemical vapor deposition on the seeds and homogenous nucleation of nanoparticles known as fines. The coated seeds are filtered, extracted, and then milled to make both battery grade material and new seed material for subsequent runs. The FBR technology can be scaled to industrial quantities, with up to 10 kg of particle production capacity.

FILMING, EMBEDDING, SPHERONIZATION

Natural graphite (NG) is the dominant anode material for lithium ion batteries today. Raw NG takes the form of flat flakes with a large aspect ratio. For battery use the pristine flakes are usually mechanically converted into spheres (spheronization) and coated with a thin film of amorphous carbon or another material. At IFE we can spheronize and coat particles using a hybridizer or with a combination of spray drying and chemical vapour coating in furnaces.

Muhammad Abdelhamid (Ph.D), **Scientist**
is a chemist with many years of research experience in electrochemistry of rechargeable batteries, and super-capacitors. His professional interests lay in the development of novel bio-based polymers for solid polymer electrolytes and organic electrode materials for Li-ion and Na-ion batteries.



STUDY EXAMPLE

Spheronization of flake-like NG microparticles is an effective strategy for developing fast-charging lithium-ion batteries. The mechanical process changes the graphite's characteristics, increasing the lithium intercalation rate to allow faster charge and discharge. Our recently purchased hybridizer smashes the particles together by a series of rotation and rolling movements to create spherical particles with smooth surface and a narrow particle size distribution. Because no heat is applied to the sample the hybridizer can spheronize materials without increasing their particle size by annealing.

Figure 1 shows NG particles with flake-like shapes and irregular sizes. The particles were initially sieved, and then speronized in the hybridizer at a rotation rate of over 10000 rpm to provide enough impact energy. The final product was smooth round particles with a narrow size distribution (Fig. 2).

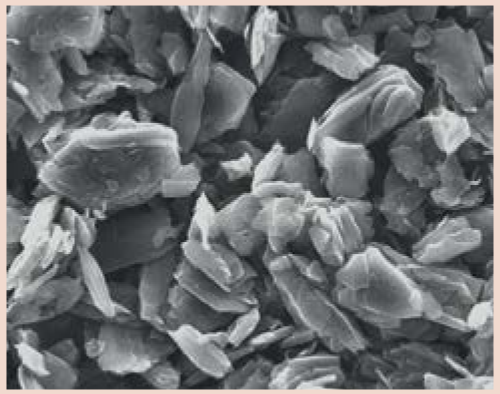


Fig. 1. Natural graphite particles are irregular in size and have a high aspect ratio.

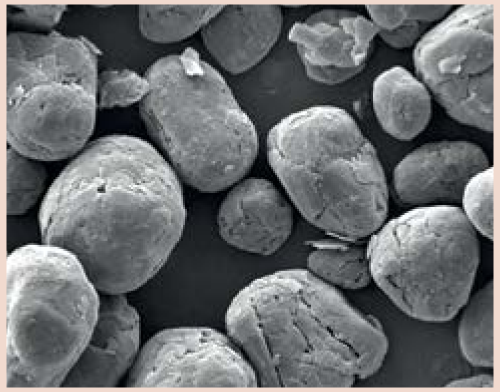


Fig. 2. Spheronization creates smooth, spherical particles.

NARA NHS-0
Hybridization System
is a microparticle surface coating and spheronizing device. **Key features:**

- Production capacity upto 50 gr per batch
- Rotation speed in range 50-2000 rpm
- Gas-tight construction
- Aqua base or solvent base formulation
- Rotor diameter 118 mm
- Short process time (1-10 min)
- Can be used for embedding, filming, and spheronizing processes.

GRINDING, MIXING

Fine grinding of the active powders can help to optimize battery performance. In many instances, batteries can be charged faster, enjoy a longer service life and higher capacity if their electrodes are composed of small particles with a well-defined size distribution. As well as tuning particle size, our grinders can be used to change the organization states and texture of powders, which also affect electrochemical properties. Optimizing the powder mixture in all of these ways enables smaller, more powerful batteries for electronics, electric vehicles, and renewable power.

Raphael Kuhn
(MSc.), **Engineer**
is a process engineer with focus on renewable resources, experienced in analytical chemistry and running pyrolysis of carbonic materials. Now working with production, processing, and characterization of battery materials.

PULVERISETTE 7
Planetary Ball Micro Mill
Key features:
- Sample quantity: 1-60 ml
- Grinding process: dry/wet
- Optimal for hard, medium-hard, and brittle materials
- Max. rotational speed grinding bowls: 2200 rpm
- Rotational speed of main disk: 150-1100 rpm
- Highest process reliability and precise reproducibility
- MillControl software enables automatic control

To achieve the best grinding results grinding balls are available in 0.1 - 20 mm diameters and in 7 different materials to prevent contamination of the samples as a result of undesired abrasion.

The concentration of particles in the slurry is typically high (between 20 and 40 wt.%). Getting a consistent and evenly mixed dispersion is important for both slurry casting and battery performance. In our laboratories we use planetary mixers to formulate or combine compounds from amounts as small as 0.5 ml to large production scale batches.

Thinky ARE-250
Planetary mixer
Key features:
- Maximum capacity: 310 g
- Multi-step mixing and de-foaming
- Container volumes: 20 and 300 ml
- Memory and step-operation functions for controlling and executing operating conditions
- Vibration and rotation speed sensors

ANALYSETTE 3 PRO
Vibratory Sieve Shaker
Key features:
- Wet and dry sieving
- Measuring range: 20 µm - 63 mm
- Max. sample quantity: up to 2 kg
- Sieve diameters: 100 mm and 200 mm
- Amplitude: 0.1 - 3 mm
- Automatic sieve analysis with evaluation software AUTOSIEVE

SEM

FIELD EMISSION SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy (SEM) is a versatile instrument for visualizing the morphology and physical structures of samples. In battery research, the SEM is often used to analyse battery materials and electrodes. For example, we can investigate particle shape, size and its distribution, and observe defects in electrodes. SEM can be also used to study porosity, pore morphology, and contaminants distribution of the separators. This helps to assess the separator quality and performance. Our microscope comprises several detectors, including the energy dispersive X-ray (EDS). EDS can detect many different elements based on their emission signatures.

Marte Orderud Skare,
(MSc.), **Ph.D. candidate**
has been working on silicon-based anode materials in our department since 2016. Her focus is on the synthesis and characterization of nanoparticles and thin films, as well as electrochemical testing of new materials.

STUDY EXAMPLE

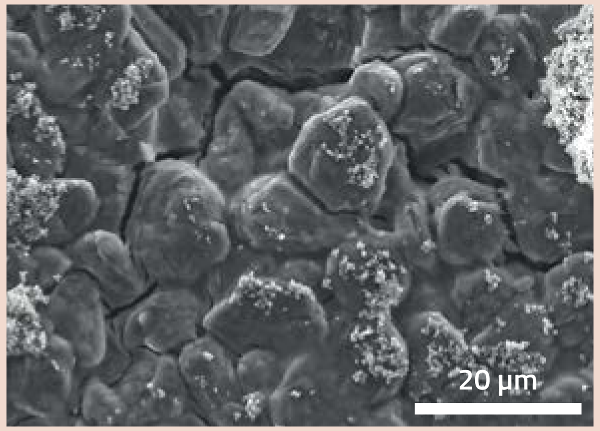


Fig. 1. Cracks in anode surface, and presence of aluminum oxide (a stabiliser) can be detected.

Batteries during their operation can experience a variety of stressors. If there is physical damage, or signs of stress, they can often be found using this method. Current collectors (foils) are often physically or chemically modified, e.g., to increase the adhesion. SEM can be used to quality control the collectors.

Fig. 2. Copper foil with dendritic pillars.

JEOL JSM-7900F Schottky
Field Emission Scanning Electron Microscope

Key features:

- In-Lens Schottky Plus Electron Gun ACL (aperture control lens) optimizes electron beam in all probe current ranges
- Super hybrid lens – provides ultra-high spatial resolution
- 4 detectors which may be used simultaneously: Lower electron detector, upper electron detector, retractable backscattered electron detector, and upper secondary electron detector.
- Super high-resolution mode provides high spatial resolution at low EV

ARGON POLISHER

In addition to investigating a specimen surface, we routinely use our SEM for observation of the specimen's cross section. This can provide important information concerning the microstructure of layered materials, composite materials, and multilayer films. Preparation of highly-polished cross section of a sample is generally not an easy task. However, with our new precision argon ion beam cross-section polisher the sample preparation is simplified, and truly representative cross sections of samples can be made without artifacts and distortions. The polisher (sometimes called an argon knife) enables a few millimeters wide and several hundreds of micron deep cuts of both soft and hard materials.

John Ostrander
(Ph.D), **Scientist**
received his Ph.D. at the University of Tulsa (USA) in materials chemistry. His expertise in materials characterization has evolved over the years from nanoparticle research to battery characterization. Primarily he works in post-mortem analysis of lithium and sodium ion batteries, and characterization of battery aging.

STUDY EXAMPLE

Broad ion beam milling utilizes ionized argon gas to bombard the sample, and physically mills materialfrom the exposed sample surface. The shielding plate is placed across the selected region of the sample that is placed inside the sample chamber. After evacuating the chamber, the region is irradiated with a broad Ar ion beam with a selectable accelerating voltage. Milling and polishing usually takes 1-2 hours and then the sample can be transferred to the SEM chamber.

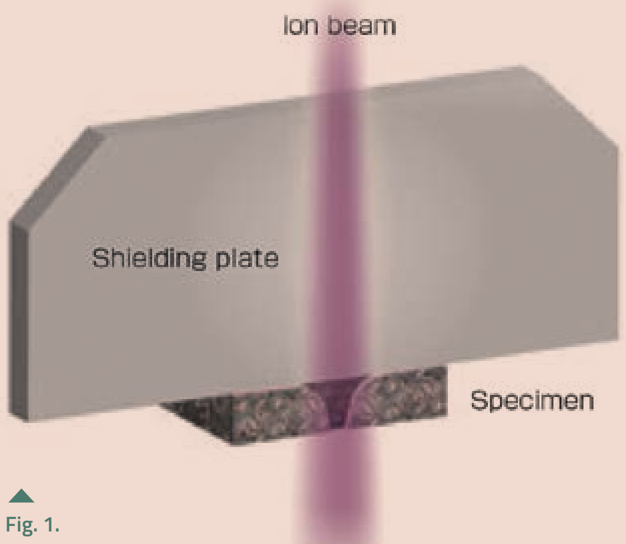


Fig. 1.
Schematic illustration of cross-section milling.

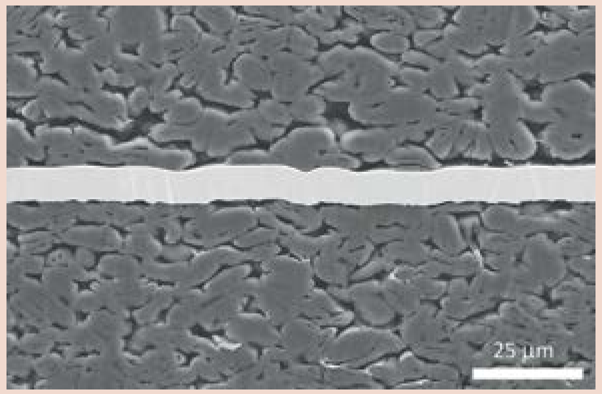


Fig. 2.
Cross-section of a double-sided graphite anode taken from a commercial electric vehicle (EV) cell that has not been used. The sample was polished using the JEOL cross-section polisher at IFE.

JEOL IB-19530CP
Argon polishing system
Key features:

- Accelerating voltage: 2 - 8 kV
- High removal rate (in Si): >500 µm/h
- Intermittend mode for temp. sensitive samples
- Gentle final milling at low accelerating voltages
- Intuitive handling using touch display
- Wealth of auto functions: start, shut down and gas flow
- Incl. holder for cross-section milling
- Additional holders opt. available for special applications

RHEOLOGY

Battery slurry characterization along the battery process chain is crucial for the reliable production of electrodes. The slurry suspension includes multiple components such as active cathode/anode materials, binder and additives mixed in solvent. Differences in slurry formulation can have a big impact on a slurry's stability and flowability.

Homogeneity, stability, and flow properties of the slurry can be investigated using rheometry. Rotational and oscillatory rheometers are well-suited for measuring these properties as they can be used to study particle sedimentation (relevant to the slurry stability), shear rate-dependent viscosity (important for the coating process), time-dependent viscoelastic properties (relevant for levelling behaviour just after coating), and more.

Particle dispersions used for fabrication of battery electrodes are non-newtonian fluids, *i.e.*, fluids with viscosity that is dependent on shear rate (or shear rate history). There are various slurry deposition methods used in academic and industrial settings to coat current collectors (metallic substrates such as copper or aluminium). Depending on the chosen method and the final design of the coating (*e.g.*, its thickness and porosity) the desired coating speed may be different ranging from 10^{-3} to 10^{2} m/s. In such range the shear viscosity may change by several orders of magnitudes affecting the coating process. Therefore, knowing the shear rate-dependent viscosity of the slurry is of importance and plays a decisive role for process control.

Zbigniew Rozynek
(Ph.D), **Senior Scientist**
is a physicist and material scientist specializing in the physics of colloidal fluids and complex matter, physics and chemistry of surfaces, as well as applied physics. Worked at Harvard University, USA, as a Fulbright scholar and now is working on developing efficient methods for fabricating battery anodes.

STUDY EXAMPLE

Battery slurries are rather complex multiphase dispersion systems. Their shear viscosities may drastically change depending on the coating velocity and wet film thickness. Typically, slurries are shear-thinning substances. But this is not always the case. Highly concentrated aqueous dispersions of graphite and silicon particles may experience **unwanted** shear-thickening behaviour in the shear rate region relevant for coating processes (usually 10 < $\dot{\gamma}$ < 1000 s^{-1}).

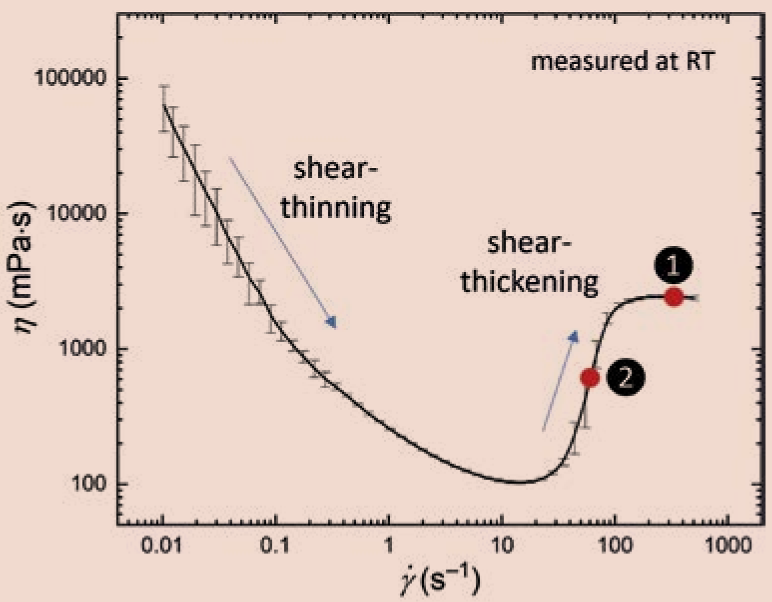


Fig. 1. Flow curve of water-based anode slurry containing silicon nanoparticles and graphite micro-particles (36 wt.%). Strong shear-thickening behaviour of observed in the shear rate range related to the coating process.

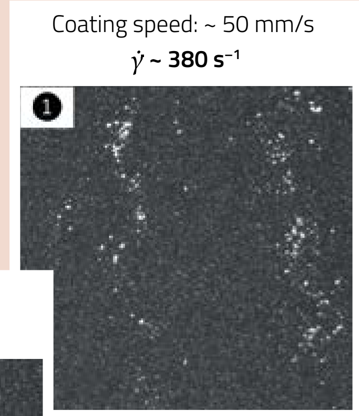


Fig. 2. Too high shear rate ($\dot{\gamma}$) leads to formation of agglomerates that are then dragged by the coating bar scraping of the material and leaving parts of Cu foil uncoated (white dots).

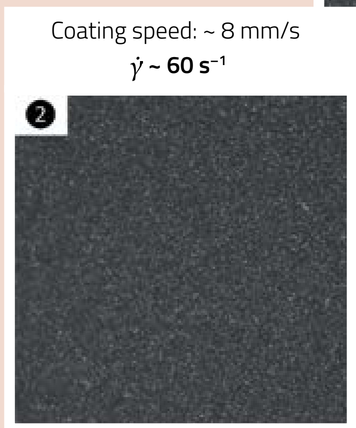


Fig. 3. Moving to lower shear rate (by changing coating speed) helps avoiding particle agglomeration and results in better quality coating (*i.e.*, the entire surface of Cu foil is coated).

Anton Paar MCR302e **rheometer**

Key features:

- Torque range 0.5-230 mNm
- Three measuring systems (cone-plate, plate-plate, cylindrical)
- Effective and convenient heating and cooling (−10 to 220 C)
- Normal force measurment upto 50 N.
- Sample-adaptive controllers (TruStrain™, TruRate™) enabling precise speed control
- RheoCompass advanced software

X-RAY DIFFRACTION

X-ray diffraction (XRD) allows us to study the structure of batteries at the atomic level. X-rays are electromagnetic waves with a wavelength similar to the length of chemical bonds. Because of this, x-rays scattered by the solid materials in a battery produce patterns which can be converted into 3D images of the atomic structure of the material that scattered them. Because every crystalline solid produces a unique XRD pattern we can use the method to identify materials and check their purity. This makes XRD a key part of electrode manufacturing process control and new materials research.

By understanding the exact structure of the electrodes at the atomic level we can tune their properties for specific applications and find new ways to modify the materials to give the best possible performance. We also use XRD to study old and damaged batteries, studying structural changes in the electrodes and identifying the chemicals formed as the battery wears out. We use this knowledge to understand and control the processes that lead to loss of activity.

More advanced XRD based methods can be used to follow structural changes in real time as we charge and discharge a battery to gain a detailed understanding of the processes that occur and identify structures which may only exist for a few seconds as the battery is cycled. If the material is not crystalline, as for several exciting electrode materials, *e.g.*, silicon, X-ray scattering can still reveal properties like particle size and, with careful analysis of the total scattering, short-range atomic structure. IFE scientists are heavily involved in developing these methods at large scale X-ray facilities like the European Synchrotron, MAX IV and Diamond Light Source.

STUDY EXAMPLE

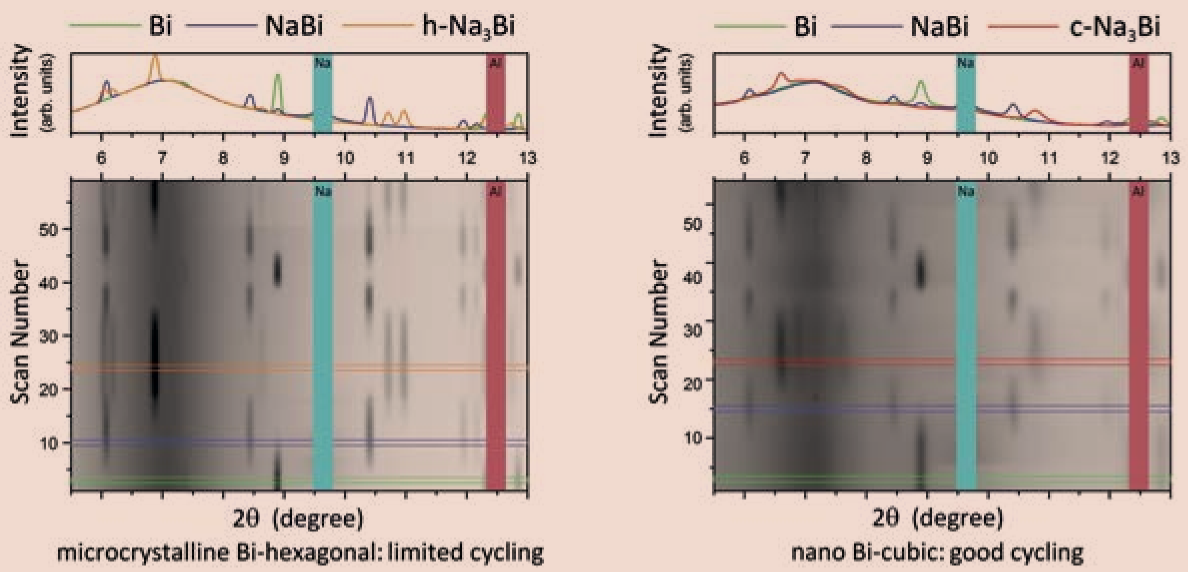


Fig. 1. Operando X-ray diffraction data showing that nano sized bismuth forms a cubic structure on sodiation, while the structure of sodiated microcrystalline bismuth is hexagonal.

David Stephen Wragg
(Ph.D), **Senior Scientist**
is a chemist who specializes in using X-rays to visualize and understand the atomic structure of working battery materials. He is a regular user of European large scale X-ray facilities and a member of access panels for several European synchrotron laboratories. His research is currently focused on understanding how lithium and sodium move through ion batteries and change their chemistry as they age.

D2 PHASER **X-ray Powder Diffraction**

Key features:

● Angular accuracy: < 0.02° ● Ultra fast 1D detector ● DIFFRAC.SUITE software ● Reusable specimen holders ● Compact size and low weight ● Sample holders for every specimen type ● Optional 6 position sample changer ● Universal design for all powder applications

SLURRY CASTING

Battery electrode films are typically made via wet electrode production, which has been the industry standard since lithium-ion batteries were first commercialized. Electrodes are manufactured by coating a slurry of active materials, conductive carbon, rheological agents, and binder onto a metallic current collector. Before coating the slurry is normally deaired and filtered to remove particle agglomerates. There are many coating techniques for manufacturing battery electrode films. At IFE we have a slot die coating unit, a screen printing machine, and various tape casting tools at our disposal.

Fig. 1. Current collector (Cu foil) is cut by hand using a scalpel.

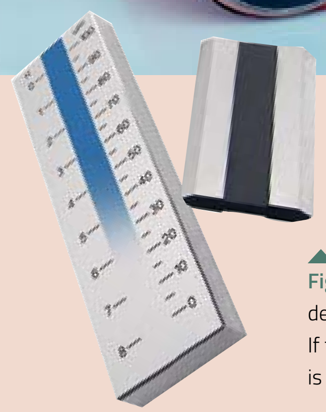
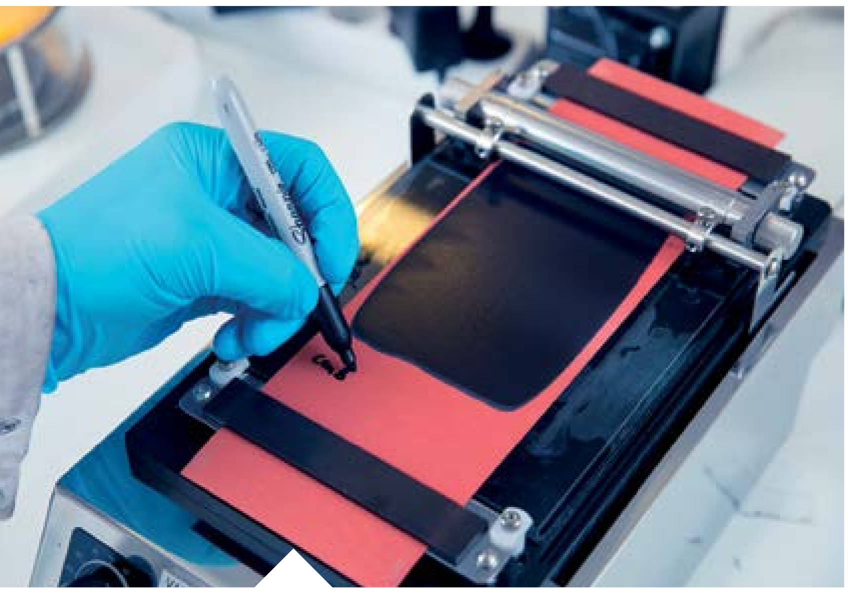


Fig. 2. Grind gauges are a common tool for determining the particle size in the mixed slurry. If the particle size is too large, the slurry is subjected to further mixing or filtered.

Marius Uv Nagell
(MSc.), **Engineer**
is a material scientist and chemist with a background in characterization of battery materials and perovskites. He investigated carbon discs and cones as anode materials as part of his Master's thesis (NTNU, Trondheim). At IFE he works on characterizing battery materials and will in the near future be involved in full cell pilot line operations.



MC-20 **Mini-Coater**

Key features:
● Coating width: 100 mm ● Coating length: 300 mm ● Coating speed: 5 to 100 mm/s ● Baker type applicator ● Thickness: 0 to 250 µm ● Built-in vacuum pump ● Simple operation

EKRA X5
Semi-automatic screen printer

Key features:
● Print speed: 9 - 200 mm/s ● Print pressure: 10 - 250 N ● Max. print format: 200 × 500 mm ● High-precision camera system ● Variety of screens enable fabrication of films with thickness 5 to 250 µm

SLOT DIE COATING

The coating of the electrode slurry is an important part of the battery manufacturing process as it has a significant impact on the microstructure of the final cast. There are several methods to coat slurry and the selection of the method is based on the properties of the slurry and the desired output. One such method is slot die coating. With slot-die coating the electrode slurry is delivered with a pump flow system and precisely coated onto the substrate through a slot die head (Figure 1).

The technique is classified as a pre-metered method as the wet film thickness of the coating is dependent on the slurry flow rate. This gives a simple relationship between coated wet film thickness, slurry flow and the speed of the coated substrate relative to the head. The method is highly flexible and can give nanometre to micrometre thick coatings, applied for a broad range of slurry viscosities while maintaining a high level of coating uniformity across the film surface. The slot-die coating is also scalable into a roll-to-roll manufacturing line (Figure 2) making the lab scale results applicable for an industrial setting.

Marta Koposova
(MSc.), **Senior Engineer**
is a chemist specializing in inorganic chemistry, synthesis and spectroscopy. Her main activities include formulation and preparation of slurries, casting of electrodes, assembly of half cells and full cells, conducting dilatometry experiments, and many more.

FOM arcRC **Slot die coater**

Key features:

- Coating area 200 x 1000 mm
- Drum enabled with temperature control
- Minimized experiment-to-experiment downtime through an active cooling system
- Multi-coating techniques equipment (slot-die coating, blade-coating, flexographic-printing)
- Lab-friendly roll-to-roll processing tool
- Multiple slot-die positions and angles
- Several shims with different widths and thicknesses

A fully assembled slot-die head consists of several key components. Namely, the front plate, back plate, meniscus guide, and a shim. The shim and meniscus guide are two thin sheets of metal between the front and back plate that serve to guide the ink to the coating edge of the slot-die head. Shim dimensions determine the final width of the coating.

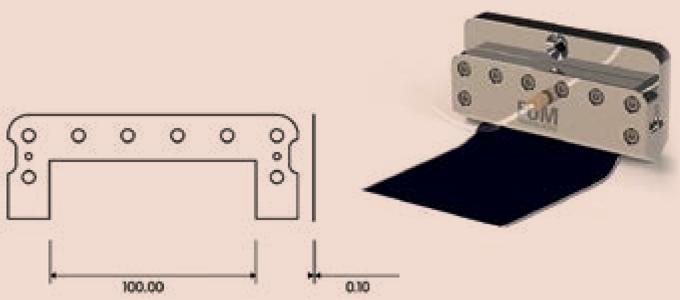


Fig. 1. Example of a shim design for producing 100-mm wide coatings (left), and an assambled slot die head (right).

Fig. 2. Graphite-based slurry being coated on carbon film (left). Silicon/graphite composite layers formed on copper metal collector (right).

STUDY EXAMPLE

CELL ASSEMBLY

In our Battery Development Laboratory, we have the capability for producing hundreds of coin cells monthly. This type of small format cell is commonly used for evaluation due to low cost and small sample sizes, also the configuration and preparation are simple. The assembly is done manually (Figure 2) inside an Argon-filled glove box, which mostly eliminates moisture and oxygen exposure (Figure 3). To achieve accurate and reliable data on new materials for batteries, quality and reproducibility of cell fabrication are critical to ensure findings. We therefore have developed detailed standard operating procedures (SOPs) to minimize as much as possible any systemic errors in the manual assembly process.

Abirdu Woreka NEMAGA
(Ph.D), **Postdoctoral fellow**
is a chemist specializing in materials for energy storage and conversion, has been working on battery research for the last 5 years. Abirdu is currently investigating silicon-based anode materials for Li-ion batteries. He is also involved in inorganic material synthesis, materials characterization, active materials electrode formulation and battery cell assembly.

STUDY EXAMPLE

Certain key factors substantially influence the performance of the final cell. Coin cell parts (metal cases, springs, spacers) are carefully cleaned before transporting them to the glovebox. Moisture content in the glove box is carefully controlled. Additionally, solvents and electrolytes are periodically checked for water content using Karl Fischer titration.

Fig. 1. Precise puncher is used to cut out disc-shape electrodes formed on Cu foil.

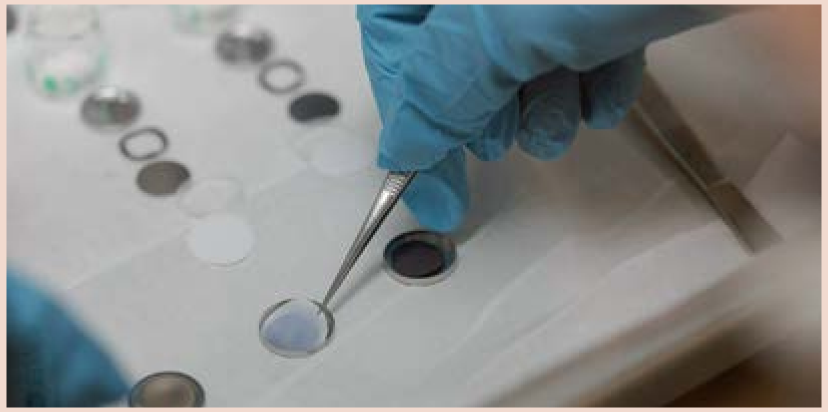


Fig. 2. The alignment of electrodes is critical for long cycling stability of the cell. Alignment also reduces inconsistent results, and cell failures during testing. Here, a separator is placed onto an electrolyte wetted anode.

Fig. 3. Manual coin cell crimper machine tool for CR2032 type cells.

After the cell is assembled, it needs to be crimped, or pressed together. When crimped, coin cells form a hermetic seal which is air-tight and necessary for performance and safety. The crimper is set to use a fixed pressure and time in order to properly seal every coin cell the same way. The finished cell can be now moved from the glovebox and inserted into one of our battery testers.

MBRAUN LABmaster pro
GLOVEBOX with Vaccum oven

Key parameters:

- Moisture 1 ppm, Oxygen 1 ppm
- Leakage Rate 0.001 vol%/h
- Clearroom SO-5
- Closed loop circulation
- Negative and positive pressure operation
- Working gas: Argon or Nitrogen
- Equipped with a high-definition, easy-to-read 7" touch screen

ASSEMBLING POUCH CELLS

Batteries with soft, polymer-coated aluminum foil casing are known as pouch cells. At our Battery Technology Department we can produce laboratory grade pouch cells with different desired capacity. We are equipped with various tools for precise cutting of cast electrodes, stacking them up, forming electrical connections, vacuum sealing and testing.

Nora Kvalsvik,
Master's student
is currently studying material science at NTNU and working on a Master's project related to cobalt-free cathode materials for lithium-ion batteries. Her lab activities include casting electrodes, assembling battery cells, electrochemical characterization, and analyzing electrodes post-mortem.

STUDY EXAMPLE

Electrode coupons for pouch cells are cut using dies with fixed sizes. Our die cutter has several rectangular dies which enables us to prepare pouch cells of different sizes and capacities.

Fig. 1.
Cutting dies for pouch cell preparation.

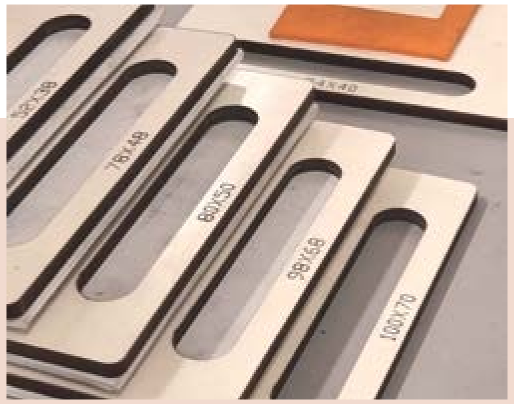
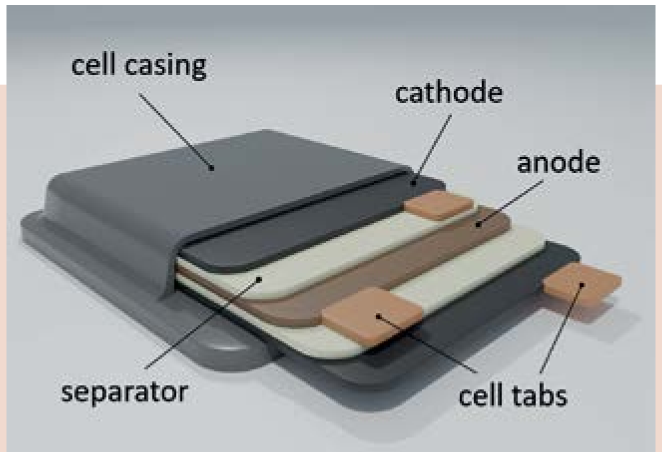


Fig. 2.
A coin cell is a single-cell battery with capacity typically < 300 mAh. A pouch cell (right) can be made of several electrode sheets, and can reach capacities hundred times that of a coin cell due to the larger size, and (if used) additional electrodes sheets.

Spot Welding Machine
for Battery Tab Welding
Key features:
- Max. output power: 1000 VA
- Working freq.: 25 kHz
- Working stroke: 15 mm
- Welding time: < 1 s
- Welding ability: multilayer Cu and Al below 0.3 mm

Each pouch has metal tabs, i.e., terminals which are connected to current collectors inside the pouch. These carry the electrical current from the electrodes. In a multi-cell battery, tabs from each cell must be connected as needed for voltage, current, or both. In our laboratory we use ultrasonic welding to join metal components in the cells. Ultrasounds create vibrations between the materials to be joined, generating enough heat to melt the metals so that they become welded together, usually very rapidly.



SMALL-SCALE BATTERY TESTING

IFE has 5 prime battery testers able to test more than 450 coin cells and pouch cells, with additional testers planned for 2023. These testers are used in a research environment for screening new battery materials and components. The most common method for studying batteries is galvanostatic cycling. A current is applied to drive an electrochemical reaction, followed by a reverse current to drive the reverse reaction. The potential response of the material is recorded and analyzed to retrieve important information about battery's characteristics and performance, including specific capacity, Coulombic efficiency, end of cycle life, electrolyte stability, and more. In our laboratories we often test new electrode materials. Typically, we start with assembling a half cell. In the half cells, the electrode material under investigation is matched against a counter electrode of pure lithium (or sodium) metal in excess to ensure enough metal ions are available to completely fill the electrode under study. Full cells on the other hand are a cell composed of the test electrode and the electrode material that is pictured to be matched against it in a commercial battery cell. If we test an anode material, a commercial cathode material like NMC could be matched in the full cell.

Carl Erik Lie Foss
(Ph.D), **Scientist**
is an electrochemist and material scientist specializing in advanced electrochemical characterization of battery materials. Experienced in developing next generation Li-sulphur technologies. Currently working on optimizing graphite and silicon-based anodes.

Arbin Instruments
MSTAT21044 **battery tester**

Key features:
● Max. voltage 5 V, Max. current 5 A ● Current ranges: 5A/500mA/20mA/1mA ● Channel Numbers: 96 ● dQ/dV & Coulombic Efficiency Measurements ● Life Cycle Testing ● PITT/GITT ● Symmetric-Cell Testing ● Half-Cell Testing and Materials Research ● Cyclic and Linear Sweep Voltammetry ● Chronoamperometry ● Chronocoulometry ● Chronopotentiometry ● Multi-Electrode Testing ● Electrochemical Impedance Spectroscopy

STUDY EXAMPLE

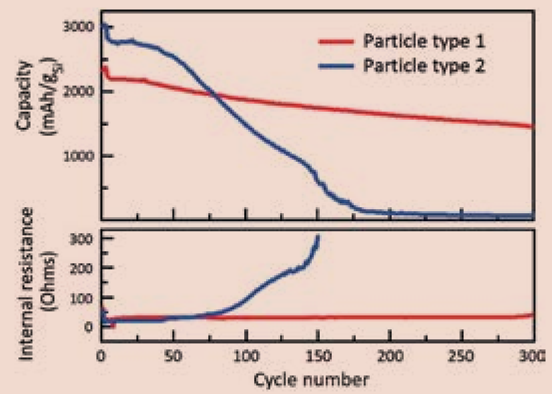


Fig. 1. Comparison of specific lithiation/delithiation capacity for two types of amorphous silicon nanoparticles (synthesized at different temperatures) measured in half-cell configuration. The difference in morphology of the particles resulted in different volume expansions, which impacts the lifetime of the electrode.

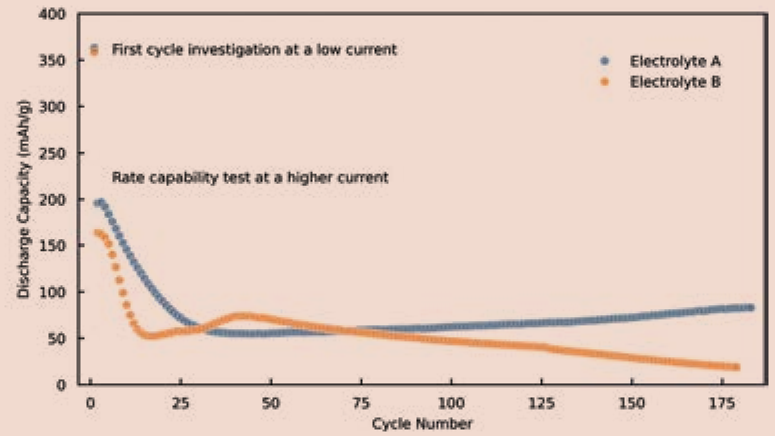
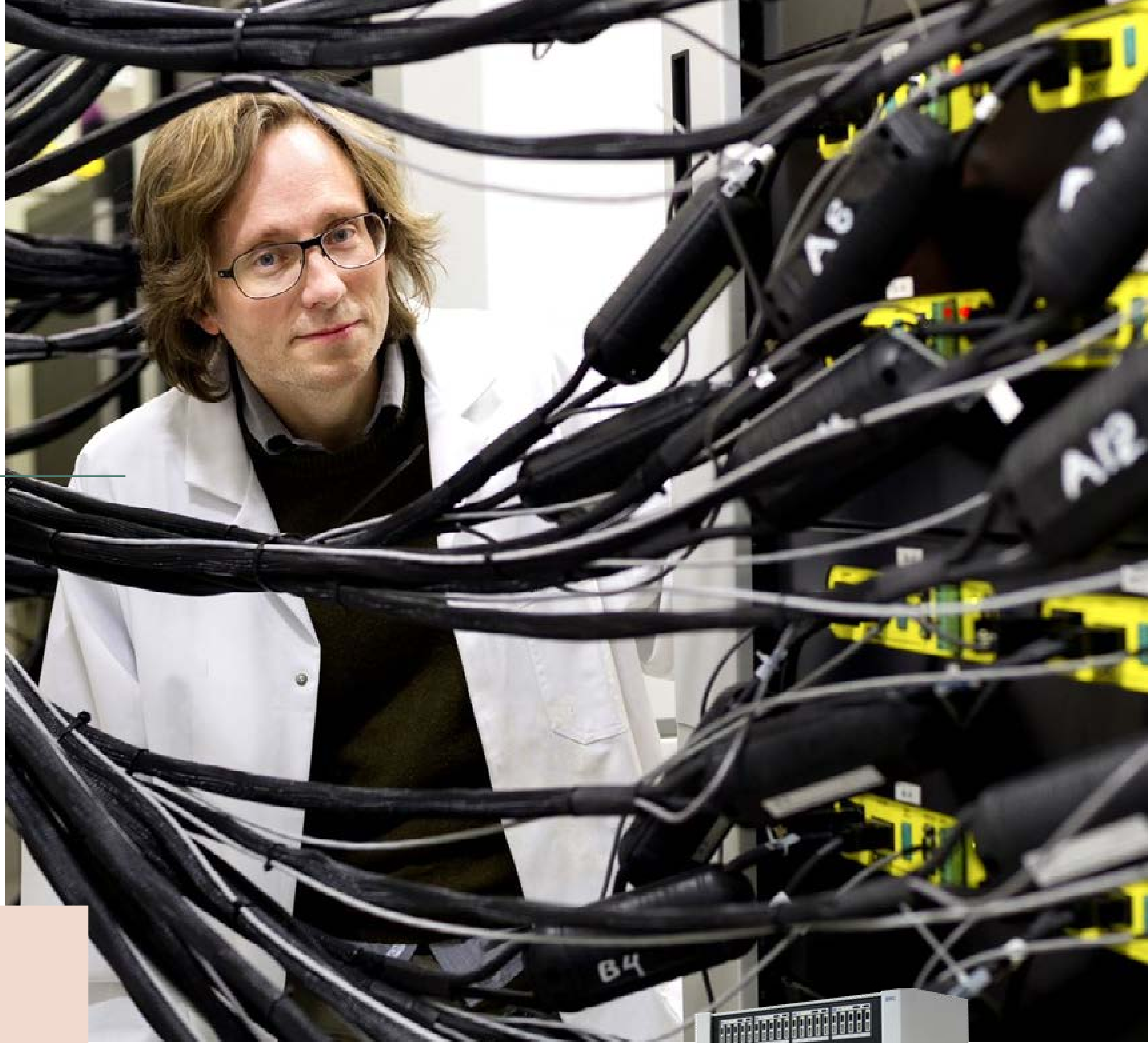


Fig. 2. A study of the cycling performance of a graphite electrode material with two types of electrolytes. Electrolyte B performs poorer, i.e., it gives a higher initial capacity loss and at around 40 charge/discharge cycles the battery's capacity decays continuously.

COMMERCIAL BATTERY TESTING

In addition to characterizing smaller lab-scale cells, we specialize in testing larger commercial cells and battery modules at our Battery Testing and Characterization Lab. This specialization has developed through a longterm cooperation with the Norwegian maritime industry, where there is a need to validate commercially available EV batteries considered for the maritime fleet. Safety and lifetime evaluation are crucial factors in this growing sector, along with risk reduction for physical installations and economic forecasts. New measurement techniques have been developed to evaluate the aging of Li-ion batteries, encompassing both natural degradation (which occurs even when the battery is not actively in use) and cycle life aging. Various parameters, such as temperature, state-of-charge, charge and discharge current, and mechanical pressure.

Preben Joakim S. Vie,
(Ph.D), **Senior Scientist**
is a physical chemist specializing in testing commercial cells and studying battery degradation. He has experience in handling and characterizing larger cells with various chemistries. Currently, Preben is working on expanding the cell testing labs and handling modules, in addition to cells.



STUDY EXAMPLE

To ensure controlled conditions, all battery cycling is conducted within temperature-controlled chambers. Larger cells undergo cycling and storage in dedicated fireproof testing and storage rooms. Our facility also offers accelerated testing capabilities and access to advanced lifetime models for comprehensive analysis.

Commercial cell testing:

Key features:
- 260 test channels (0-5 V, 0–50 A)
- Temperature chambers from -40 °C to 80 °C
- Constant current, power, voltage and resistance cycling
- Emulation of drive-cycles

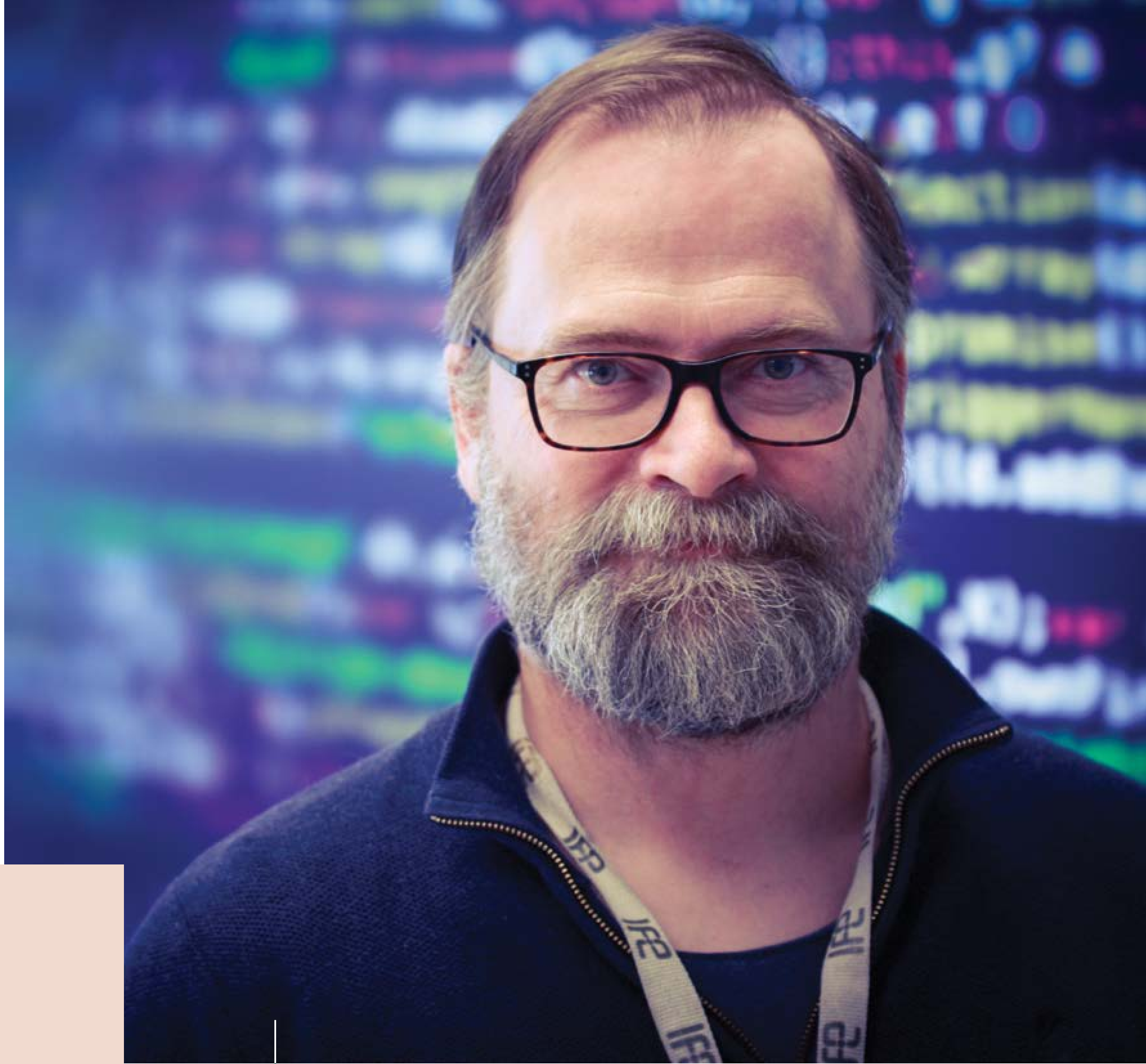
Characterization of degradation with:
- Charge and discharge curves
- Current pulse characterization
- High precision Coulombic efficiency cycling
- Entropy spectroscopy
- dQ/dV (incremental capacity analysis)
- Electrochemical impedance spectroscopy

DATA HANDLING

The long-term performance of a battery is usually shown as a plot of capacity vs cycle number. Most cell cycling instruments provide this data in a format which is straightforward to plot and adjust, *e.g.* to the weight of the battery (gravimetric capacity) or its size (volumetric capacity). But cell tests often contain a lot of other information which can be extracted with reference to charge rate, response time and in some cases external information like cell temperature. By looking more closely at the data we can gain a deeper understanding of the battery. Unfortunately, different brands of instrument handle the digital information in different ways and store it in different formats.

To compare many cells tested under different conditions and with a large variety of additional meta-data (type of cell, type of chemistry, electrode properties, etc.), we need more advanced data handling methodologies. One of the important steps in most data handling is homogenizing the data-pulling together information from multiple sources and ensuring that it is consistent, accurate and comparable. This can be a challenging task (see fact box 1).

At IFE we have developed our own suite of open-source software to achieve this. CellPy [https://github.com/jepegit/cellpy/], can directly parse the data from most commercial battery testing units, as well as reading user defined text and spreadsheet formats. It converts and saves the data in a common format so that subsequent data handling becomes considerably easier. As well as translating to the common format, cellpy has a range of utilities for studying the data, including: extraction of key characteristics from the tests, calculation of derivatives, cell comparison, plotting and statistical analysis.



cellpy

https://github.com/jepegit/cellpy

CellPy helps users from data collection to visualization

- Data collection: Different battery testing instruments use different methods for measuring the same parameters, and different test conditions can produce different results. This can make it difficult to compare results from different tests.
- Data cleaning: Cleaning the data involves identifying and removing any errors or outliers and making sure it is complete and consistent. This is usually done manually by scientific experts.
- Data normalization: Normalizing the data means converting the different types of data into a common format and with matching units for reliable comparison and analysis. Normalization requires us to understand both the individual variables and the relationships between them.
- Data analysis: Once the data has been cleaned and normalized, it can be analyzed to identify patterns and trends. However, the amount and complexity of the data can make it challenging to extract meaningful insights and conclusions.
- Data visualization: good visualization is essential to effectively convey results and interpretation in a clear and concise manner while maintaining accuracy and relevance.

Jan Petter Mæhlen
(Ph.D), **Group Leader**
is a theoretical and experimental physicist with more than 10 years of experience in battery research. He leads the Battery Development Group, the members of which work on understanding and developing new materials for lithium-ion batteries. Jan Petter is the main developer of the cellPy Python package for user friendly and efficient handling and interpretation of data from electrochemical testing of batteries and cells.

python™

COMSOL **Software**

Key features:

- Battery Design Module
  (an add-on to the COMSOL Multiphysics® package))
- Encompasses descriptions over a large range of scales
- Enables solving the detailed structures in the battery's porous electrode
- Includes physics phenomena such as:
  – transport of charged and neutral species,
  – charge balances,
  – chemical and electrochemical reactions,
  – Joule heating and thermal effects due to electrochemical reactions
  – fluid flow, and other physical phenomena related to battery systems

PyBaMM **Software**

Key features:

- Solves physics-based electrochemical DAE models
- Uses state-of-the-art automatic differentiation and numerical solvers
- Doyle-Fuller-Newman model can be solved in under 0.1 seconds
- Reduced-order Single Particle Model and Single Particle Model with electrolyte can be solved in just a few milliseconds
- Additional physics can easily be included such as thermal effects, fast particle diffusion, 3D effects, and more
- All models are implemented in a flexible manner
- A wide range of models and parameter sets (e.g., NCA, NMC, $LiCoO_2$) are available

MODELLING

Computational modelling is a powerful and valuable tool for understanding lithium-ion batteries. It serves multiple purposes: assisting the analysis of experimental data, performing virtual experiments to guide the battery development process, and monitoring and managing working batteries. Different applications require different approaches and levels of complexity: in battery design and development, a high level of detail and accuracy is desired (at the cost of longer simulation times), while real-time monitoring and management of battery performance require simplified models that use less computational power.

Julia Wind
(Ph.D), **Scientist**
has a background in mathematics and materials science, with a special focus on structure-property relationships of functional materials using combined experimental and computational approaches. At IFE she is currently working on battery modelling, employing both mechanistic and empirical approaches.

STUDY EXAMPLE

Mechanistic battery modelling
Physics-based electrochemical battery modelling provides detailed insights into the processes in a battery giving a fundamental understanding of the working principles and degradation mechanisms of new materials as well as commercial Li-ion cells. The models are based on mathematical equations combined with appropriate boundary conditions and require physical input parameters describing the battery materials and design. They provide qualitative and quantitative behavior predictions.

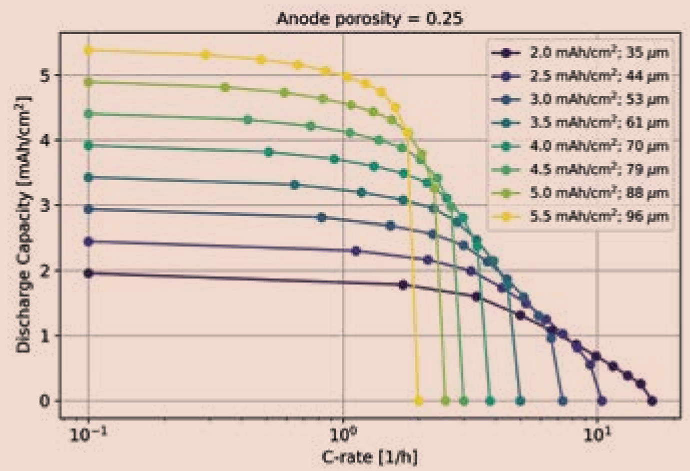


Fig. 1. Simulated areal capacity vs C-rate for a selected anode porosity.

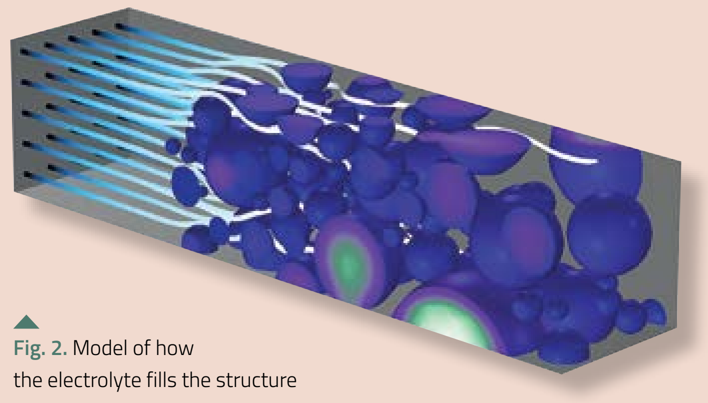


Fig. 2. Model of how the electrolyte fills the structure of a porous electrode in a battery.

Empirical modelling
Empirical models are the simplest (and computationally cheapest) type of battery models. They are based on fits of model equations to selected battery data and targeted to very specific applications. Making use of the vast amount of battery cycling data collected over many years at IFE, we have developed, fitted and tested an empirical ageing/SOH prediction model which functions over a wide range of experimental conditions.

IMPEDANCE SPECTROSCOPY

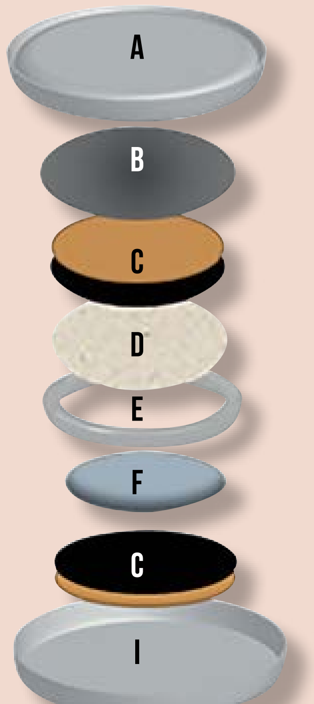
Electrochemical impedance spectroscopy is a powerful tool to investigate the electrochemical processes inside the battery. It gives information about a wide range of processes such as electronic resistivities, diffusion processes, charge transfer resistances of both electrodes, interfacial resistances, ionic resistance in the porous electrodes and separator.

As demands for high power and high energy density grow the material loading must increase while keeping the battery performance. One of the main factors influencing the Li-battery performance is the ionic resistivity of the electrode. With increasing materials loading, this resistance grows.

Based on our knowledge of Li-ion movement inside porous graphite electrodes during charging and discharging, a microstructure that gives the shortest path length to the graphite layers is favourable. This is described by the geometric parameter tortuosity which can be defined as the shortest connection between two points compared to the length of the straight connection between these points. There is a clear correlation between electrode tortuosity and its performance inside a cell. Through relationships, the tortuosity measure is derived from the impedance response of the electrodes. When testing new graphite materials and optimizing the slurry recipe, impedance spectroscopy gives the initial screening, requiring less than 10 min per test. In comparison, cycling tests takes months. Based on the results, the electrodes with lowest tortuosity can be selected for further cycling tests.

Theresa Nguyen
(MSc.), **Engineer,**
is trained as a chemical engineer and biotechnologist. At IFE working on investigating new carbon-based anode materials for Li-ion and Na-ion batteries, and is interested in electrochemistry.

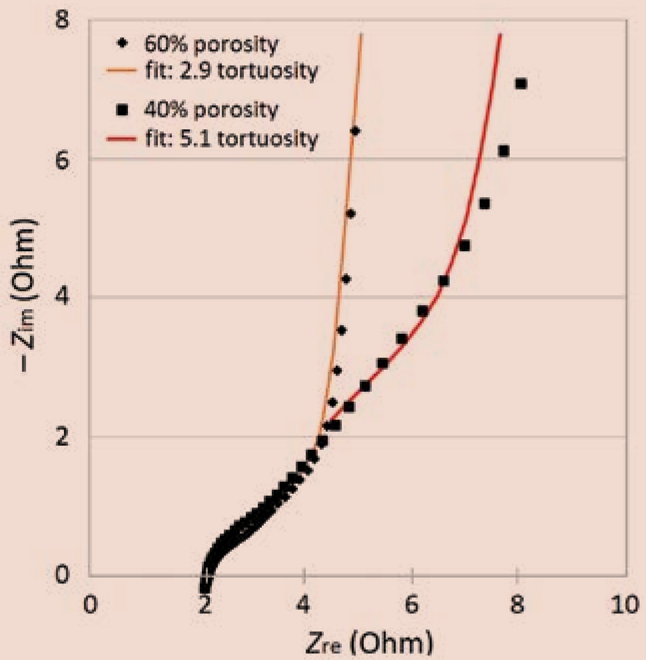
STUDY EXAMPLE



For microstructure studies, the electrodes are assembled in symmetric cells with a non-intercalating electrolyte. This prevent impedance contributions from charge transfer reactions and the ionic resistance in the porous electrodes can be easily extracted.

Fig. 1.
Blow out illustration of a symmetric cell
A – coin cell cap
B – spacer
C – graphite electrode
D – separator
E – gasket
F – electrolyte
I – coin cell can

Fig. 2.
The Nyquist graph shows the plots of two different porosities and their fitting to a semi-diffusion circuit model for an electrode material. The tortuosity is derived based on the ionic resistance extracted from the fitting and relating the geometric parameters porosity and tortuosity to electrical parameters using Ohms law.



BIOLOGIC SP-300 **Potentiostat**
Key features:
● 2 channels ● Current range of 500 mA to 10 A ● Voltage resolution from 1 μV to 60 mV range ● Built-in EIS with 7 MHz max frequency ● Floating mode, analog filtering, built-in calibration board, stability bandwidths ● Multiple user system ● Optional high current/high voltage option board

ADVANCED BATTERY CELL PROTOTYPING LINE

nabla lab

Norwegian Advanced Battery Laboratory Infrastructure

A new Cell Line Lab for making, testing, validating and prototyping of batteries is under construction at IFE, Kjeller. The lab will have an area of approximately 500 m^2 and provide IFE with a wide range of new and improved facilities. The laboratory is part of the newly established national research infrastructure NABLA (National Advanced Battery Laboratory) co-funded by the Research Council of Norway.

The new lab we will have a pilot-scale production line for two different sizes of pouch cells (1 Ah and 10 Ah) using the same methods found in Li-ion battery factories around the world. The lab will also have space for conducting research with the latest cutting-edge materials in smaller cells.

The Cell Line Lab will enable in-depth optimization studies of all stages of battery production, from component preparation to assembly and testing, providing vital information for cell manufacturers. While doing this, the lab will provide opportunities for training the next generation of battery researchers and engineers.

*The Cell Line Laboratory will be commissioned in Q3, 2023 and fully operational in Q4, 2023.

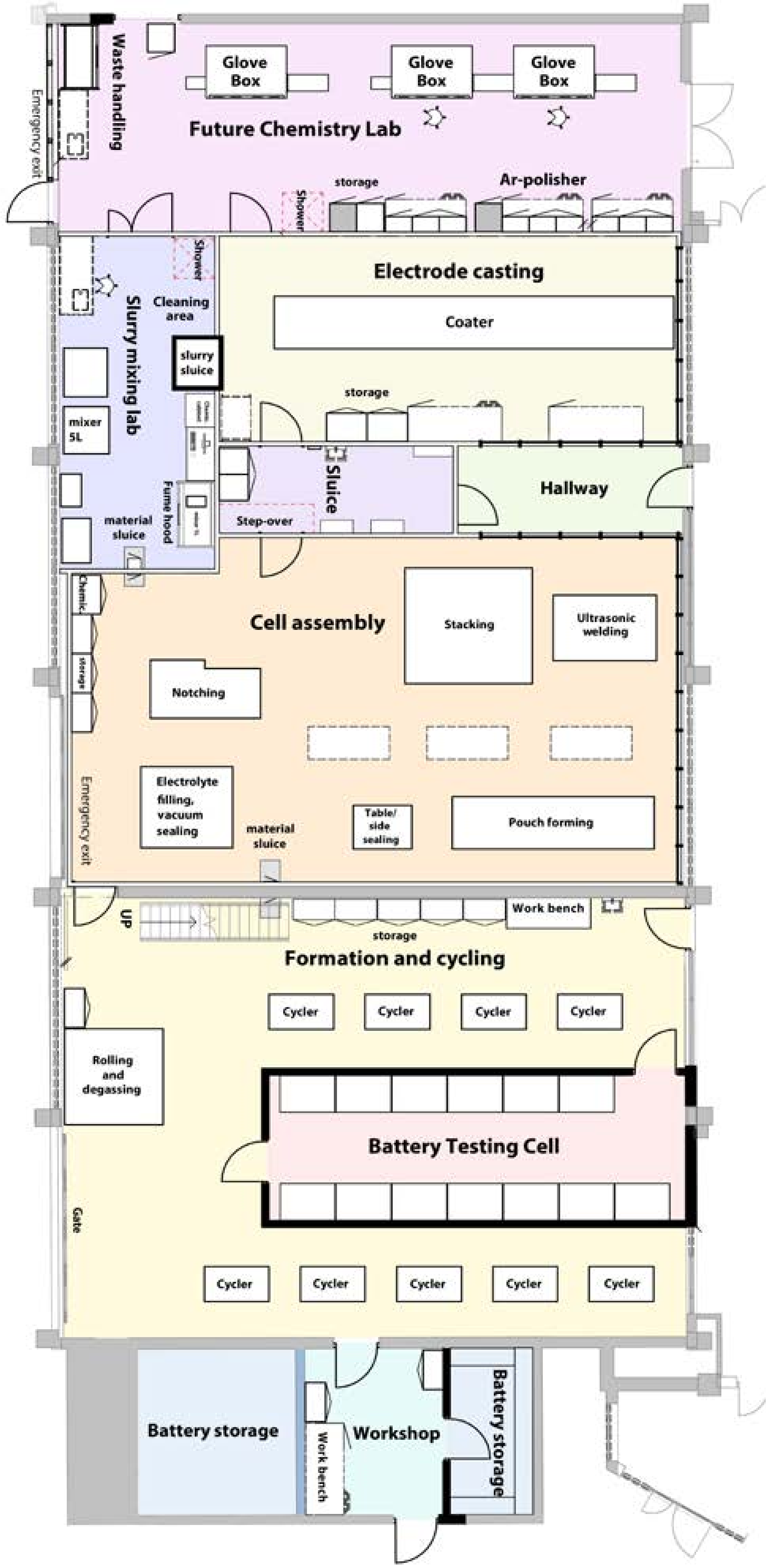
Going in to the new lab, the first room you will enter is the New Chemistry Laboratory, equipped with argon filled glove boxes where air sensitive and novel battery research will be performed. Continuing further in, you enter the Slurry Mixing Laboratory. Here you will find equipment for mixing the battery materials with additives and binders, creating the slurry that later will be cast on to metal foils to make electrodes. Understanding the properties of the slurries and tuning their viscosity and homogeneity through different mixing procedures will enable perfect electrode production. Advanced mixers, and a state-of-the art rheometer, will give us the reliability, scalability, and flexibility we need.

When the desired slurry is prepared, it can be transferred through the sluice cupboard into the Electrode Coating Laboratory. This is one of two clean rooms in our new lab. The clean environment ensures the quality of our electrodes by preventing contamination.

The electrode slurry is coated onto a roll of metal current collector foil (typically Cu foil for anodes, and Al foil for cathodes) and then dried by passing through three oven units. The electrodes are then calendared (pressed) to the required thickness (monitored using a 2D laser system) giving a smooth, flat surface, before being sliced to the required width and re-rolled. Our electrode coater will perform roll-to-roll coating with anything from a few grams to several kilos of electrode mixture.

Through the sluice you enter the Cell Assembly Laboratory. This is both a clean room and a dry room, to prevent moisture and dust damaging the battery. Here, the rolls undergo the notching step, in which electrode sheets are stamped out and dried. Next an automatic stacking machine stacks alternating layers of positive and negative electrodes separated by thin, porous sheets to prevent direct contact between the electrodes. Metal contact tabs are ultrasonically welded onto the stack before it is placed in a foil pouch. Finally, the pouch is filled with electrolyte and vacuum sealed.

The final section of the new lab features state-of-the-art test facilities for cycling and assessing the performance of the assembled battery. Now, the battery can be cycled, and its performance can be monitored using a range of electrochemical and structural tools.

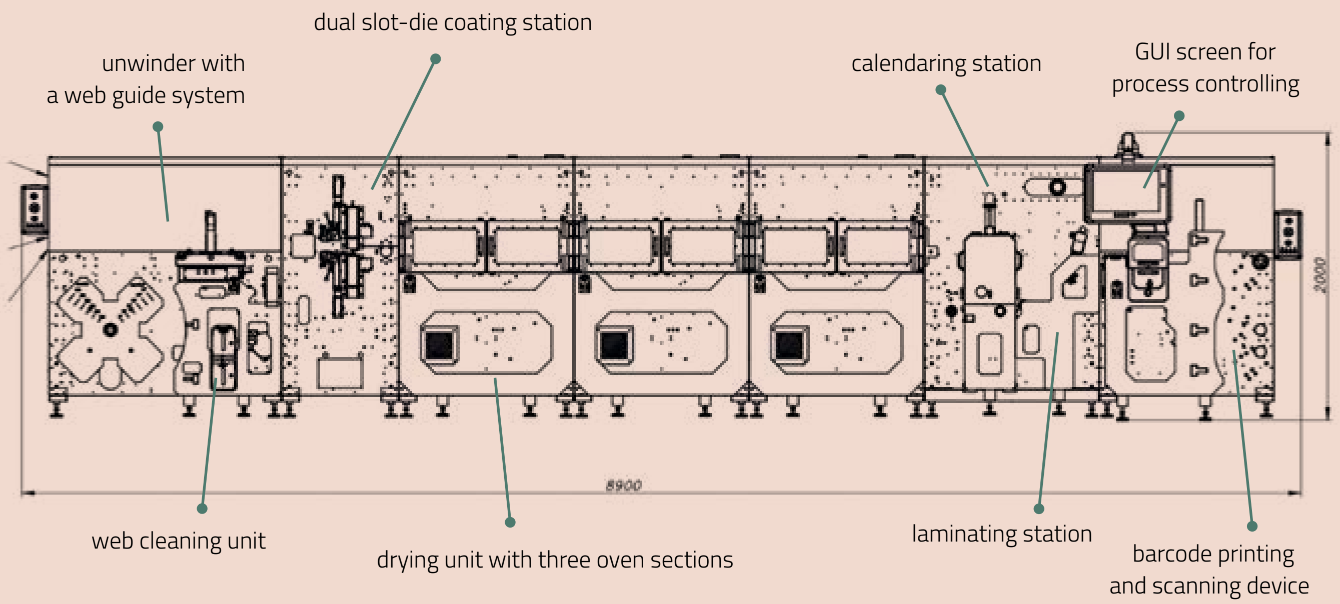


NEW COATING UNIT FOR BATTERY ELECTRODE PRODUCTION

In Dec 2022, IFE researchers from Battery Technology Department went to Warsaw, Poland to witness Factory Acceptance Testing (FAT) of the new coating unit for battery production that will soon be delivered to Norway. The FAT helped verify that the newly manufactured and assembled equipment met its intended purpose and complied with the contractual specifications.

The FOM moduloR2R (designed and developed by FOM Technologies in Denmark and manufactured in Poland) is a highly capable, modular roll-to-roll coating unit. The base model consists of unwind, rewind, oven and slot die stations for a pilot-scale battery electrode production, representing an ideal first step from research and development toward full-scale fabrication. The coater provides process control through a digital platform, which ensures greater reproducibility and quality assurance. The process parameters are automatically logged by the control software, with export functionality for further data analysis, and can also be labeled via barcodes alongside the coated area by a synchronized printer.

Jan Petter Mæhlen
(Ph.D), **Senior Scientist**
is the main driver of the NABLA prototyping line. Over the last 4 years he has been involved in all stages of the project from securing funding and designing the lab to selecting suppliers and testing equipment.

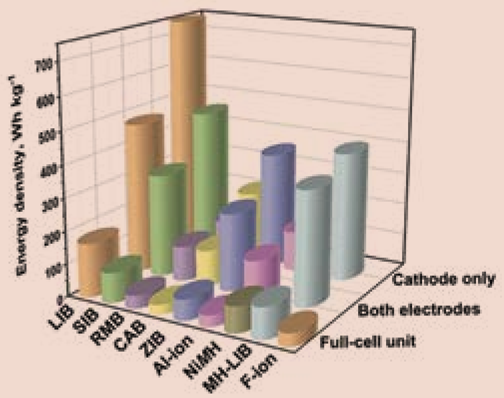


Martin Kiener (FOM Technologies) run multiple tests on the FOM moduloR2R coating unit to check how well the coater will function in its future operating environment at IFE. Theresa Nguyen (IFE) witnesses the FAT of one of the core pieces of equipment comprising IFE's new Battery Cell Laboratory.

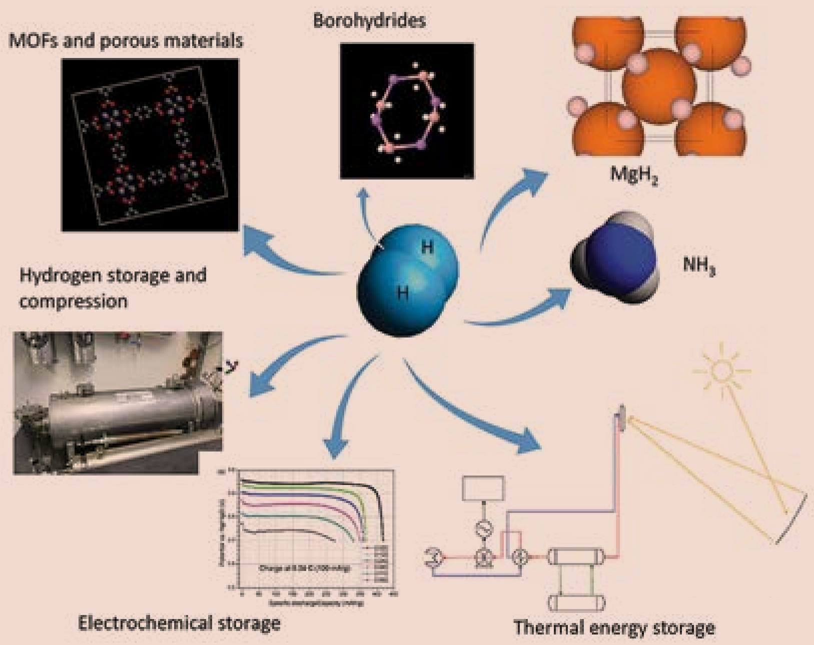
Volodymyr Yartis
(Ph.D), **Senior Scientist**
is an expert in hydrogen-based energy storage and secondary batteries. He authored more than 300 papers. Volodymyr is on the Stanford University List of Top 2% Scientists Worldwide, 2022, and is within 40 best Chemistry Scientists in Norway (Research.com). He is a project leader in the projects funded by EU, Norwegian Research Council, Nordic Energy Research, INTAS, NATO and industry. Volodymyr is the editor of J. of Alloys and Compounds, International J. of Hydrogen Energy, and journal Batteries. Yartys is a representative of Norway in the International Society of Electrochemistry.

The battery market is rapidly growing due to the increasing need for mobile devices, electric vehicles, and energy storage systems during the energy transition. The review article titled *Exploits, Advances and Challenges Benefiting Beyond Li-ion Battery Technologies* focuses on post-Li-ion technologies such as Na-ion, Mg, Ca-ion, Zn-ion, Al-ion, and anionic shuttle batteries. It also highlights MH-based batteries, particularly NiMH and MH-accommodated Li-ion batteries.

Globally, the increasing use of renewable energy sources has sparked research in renewable energy production, storage, distribution, and end-use. The review article titled *Materials For Hydrogen Based Energy Storage* focuses on hydrogen as a clean and efficient energy storage vector. The review provides an overview of the current state and future prospects in areas such as porous materials, liquid hydrogen carriers, complex hydrides, intermetallic hydrides, hydrogen energy systems, and research outlook for hydrogen-based energy storage.



Exploits, Advances and Challenges Benefiting Beyond Li-ion Battery Technologies *J. Alloys and Compounds*, **817** (2020) 153261.



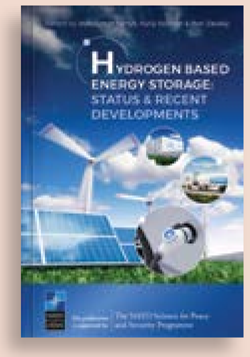
Materials For Hydrogen Based Energy Storage – Past, Recent Progress And Future Outlook. *J. Alloys and Compounds*, **827** (2020) 153548.

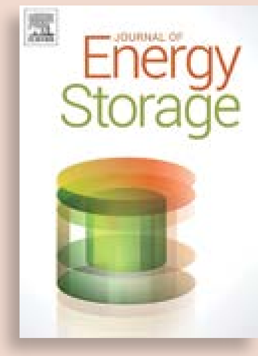
PUBLISHING

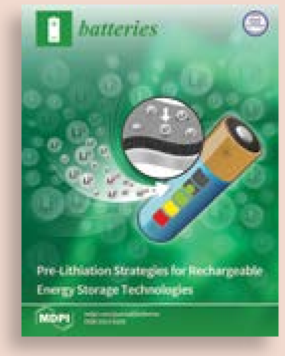
Publishing scientific research is a crucial part of the way in which science progresses by sharing ideas and building on existing knowledge. Publicly funded research projects are usually expected to produce publications as a condition of funding. This is because such projects are typically conducted with the goal of advancing knowledge and benefiting society. IFE has policies and guidelines for publishing scientific articles that are intended to ensure that research conducted by IFE personnel is executed ethically and in accordance with best practice in the respective fields. We also ensure that research findings are disseminated in an appropriate and timely manner.

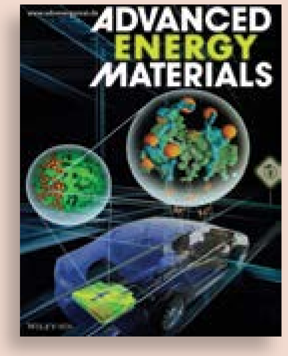
At the Battery Technology Department, we recognize that the benefits of publishing scientific articles extend beyond the research community. Battery technology plays a significant role in the development of renewable energy systems and the transition to a more sustainable future. Publication and dissemination of research findings are instrumental in informing policymakers and educating the public about scientific progress in battery and energy systems development. This raises awareness of the potential of battery technology, and the importance of continued investment in research; accelerating the adoption of sustainable energy systems, which can reduce greenhouse gas emissions and mitigate the impacts of climate change.

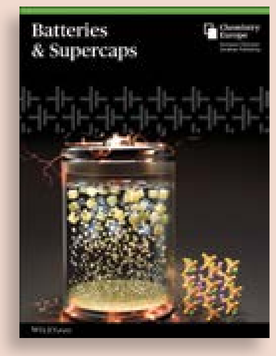
An informed dialog with society is essential to build a consensus for the green transition. Because of this we publish popular articles alongside our technical papers, to make complex findings more understandable. Members of our department also appear in media discussions and debates. This helps foster greater engagement and understanding between academics, policy experts, and the general public.











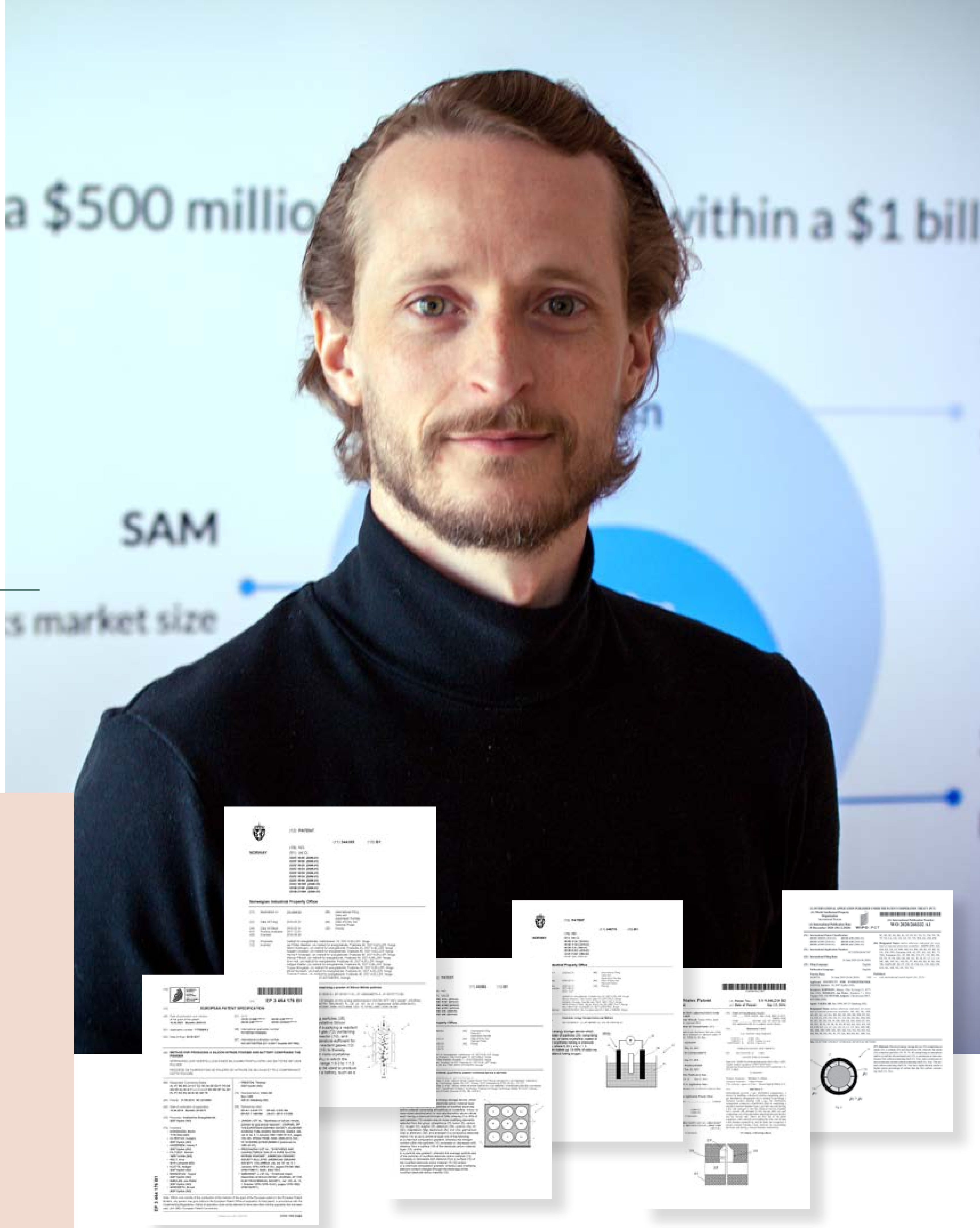
INNOVATION

The prerequisite of the commercial success is the securing of the intellectual properties. At IFE we have effective intellectual property rights strategies to protect our inventions. Several members of our Department have practical knowledge on drafting patent applications. Some of our colleagues have also entrepreneurial experience which is valuable for quicker perceived new venture creation. We recognize that innovating and commercializing the research results constitute the third pillar of financial prosperity and offer opportunities for developing new research directions.

IFE has a long tradition of commercializing ideas from research. For several years, we have been developing tools to stimulate, encourage, and support innovative behavior. We collaborate tightly with IFE Invest AS and Kjeller Innovasjon that assist with maturing our ideas, seeking funds, and help establishing and developing spin-off companies.

At the Battery Technology Department, we have recently made several discoveries that we persuade commercializing. For example, we have developed a new silicon alloy (named SiliconX) that can be used as an active material for battery electrodes. Our developed SiliconX alloy provides superior stability throughout charging cycles compared to pure silicon materials.

Asbjørn Ulvestad
(Ph.D), **Scientist**
is a materials scientist and physicist specializing in battery materials development, advanced characterization, and data analysis. He heads the commercialization effort of the silicon nitride-based anode materials that he co-invented the during his Ph.D., for which he maintains a number of patents and patent applications.



STUDY EXAMPLE

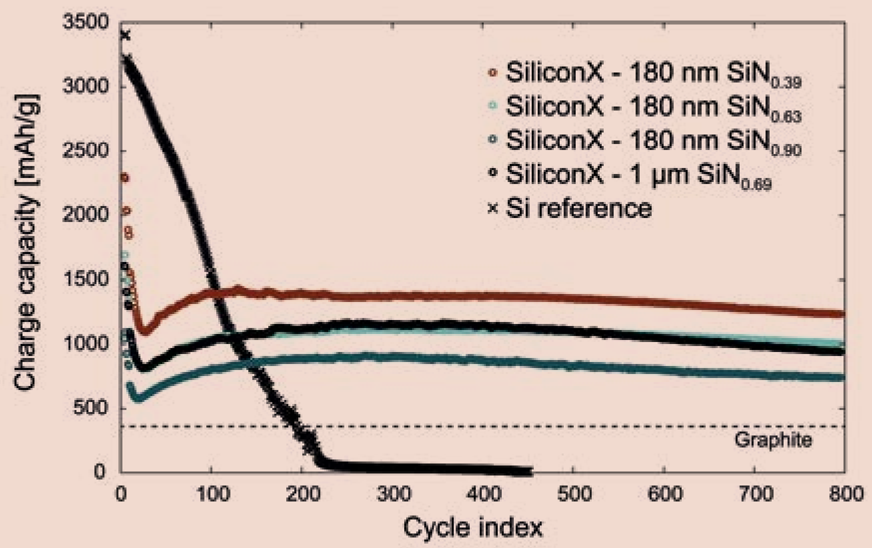


Fig. 1.
The experimental results demonstrate that, although the new battery design compromises initially on capacity, it exhibits remarkable stability throughout charging cycles. As a result, it ends up with significantly better capacity than a fast-degrading pure silicon anode and boasts three to five times the charge capacity of the graphite anodes commonly used in today's batteries.

Market overview and analysis

A key part of the business development activities is to follow the market, to understand which areas to focus on in the future, as well as scout for possible commercialization activities based on IFE research. Relevant roadmaps contribute to a direction and balance between short-term industry projects as well as building internal competence that is relevant in the long-term.

Representing IFE at EU level

As part of the European research ecosystem, the business developer is highly involved in representing IFE at the EU-level. Following up partnerships such as the Batteries Europe Association (BEPA), European Energy Research Alliance (EERA) and the Energy Materials Industrial Research Initiative (EMIRI) are key tasks for the business developer.

Being a link between research and industry

Attending industry events, hosting visits to IFE and keeping close bilateral contact with industry is crucial to understanding how the battery research at IFE can contribute the most to solving relevant problems faced by the industry.

INDUSTRY COLLABORATION

Sigmund S. Kielland
(MSc.), **Business developer**
has an education from nanotechnology and professional experience from consulting. He is well equipped for linking the battery research at IFE to the industry needs.

FME MoZEES

Research centre for Zero Emission Mobility: This research centre is coordinated by IFE, and is researching battery and hydrogen value chains for zero emission mobility. New battery materials, degradation and systems integration are key areas where IFE is contributing, and having the overview of the zero emission mobility research as a whole.

SIMBA

Sodium-ion and sodium-metal batteries: With 14 other partners, IFE is working in the EU-project SIMBA to develop sodium-ion batteries as an alternative to lithium-ion batteries as they use more abundant materials from biological sources.

SUMBAT

Sustainable Materials for Battery Value Chain: In this Green Platform project of 100 MNOK, IFE will contribute to the strengthening a competitive and sustainable Norwegian industry for battery materials. IFE's activities in SUMBAT are developing silicon and graphite anodes, testing LNMO cell system, battery degradation, reuse and recycling.

BATTMARINE

Safety and Modelling of aged Li-ion Batteries: The electrification and hybridization of ships with Li-ion batteries is an important business area for Norwegian industry. The consequences of a fire in such a system can be catastrophic. The degradation and ageing of Li-ion batteries will in many cases contribute to reduced thermal stability, and how this affects safety is investigated in this project.

2ND LIFE

- the value of Second Life batteries in the future energy system: This project identifies and quantifies possibilities and obstacles connected to the possible second life of batteries in the Norwegian energy system. The potential of used Li-ion batteries, degradation and aging models and risk assessments are key elements.

Current projects:

LongLife, MoreIsLess, 2ND LIFE, BattMarine, Seamless, Coulombus, SUMBAT, LIB Reuse, BattSeal, SiliconX 2.0, SIMBA, CoFBAT, BALSA, HEROES, Salamander.

Past projects:

BATMAN, Silicon on the road, SAIL, SiNODE, SiBANODE, SiCANODE, NatBatt, DOVRE, HAST.

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