Annual Report

INSTITUT CARNOT
Energies du Futur

cea liten

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Director's foreword

Dear CEA-Liten employees, partners, and friends,

Once again, I am proud to present CEA-Liten's Activity Report, and hope that you will be as excited as I am about our accomplishments over the past year. Decarbonization is the cornerstone of French and EU energy policy, and our research is built on a shared commitment to a Net Zero future. Energy research at CEA-Liten supports the CEA's broader, integrated vision of energy. We believe that low-carbon energy, be it renewable or nuclear, is vital to fighting climate change.

This year, as in past years, our research has helped support domestic and European industry-building efforts and, more generally, greater energy independence. We have also witnessed the unprecedented rollout of certain low-carbon energy technologies on a massive scale worldwide. This movement must be intensified, of course. But further energy savings and efficiency measures will also be needed if we are to reach the targets in the Paris Agreement.

Our vision and our experiences over the past 20 years have positioned us to face the future, to size up the challenges ahead, and to innovate the necessary solutions. Over the past several years we have demonstrated our strong commitment to innovation and technology transfer with a particularly dynamic startup strategy. We have also seen several of our strategic partners prepare to bring their products to the market, building factories in France and other European countries. This is a source of pride for us.

Our R&D activities are guided by the quest for components and systems with improved energy efficiency and performance, lower costs and environmental impacts, and circularity of materials and carbon. All in service to our industrial partners and to society.

Finally, I would like to express my sincere thanks to everyone at CEA-Liten. Your energy and commitment are central to our success. Working with you is both a pleasure and an honor.

François Legalland
Director, CEA-Liten

About CEA-Liten

CEA-Liten was founded in 2004. In the space of two decades, it has become one of Europe's leading centers for energy R&D, driving the development of competitive, responsible, low-environmental-impact energy solutions.

Our research addresses both technologies and components for the energy transition—and their integration into modular, optimized systems and grids.

With facilities on the CEA campus in Grenoble and on the INES (France's national solar energy research institute) campus in nearby Chambéry, CEA-Liten's research supports innovations that will enable a Net Zero future and creates economic value by transferring the solutions developed to companies for commercialization. Our strong commitment to the energy transition is backed by innovations in solar energy, batteries, hydrogen, sustainable chemicals and fuels, and multi-vector energy systems. Energy efficiency and the circular economy are the through-lines of all of our research.

We are innovating and creating value across all energy-transition-related markets to drive progress toward the objectives outlined in France's national low-carbon energy strategy and the France 2030 investment plan as well as in other national and EU policies. As a research & technology organization (RTO), we are also dedicated to transferring new technologies to industry through partnerships with businesses, a commitment that has earned CEA-Liten the recognition of the Carnot Network since 2006. ■

2023 key figures

1,000 scientists, engineers, technicians, and support staff

200 scientific publications per year

200 PhD students and post-docs

€160 million annual operating budget

200 partner companies

12 technology platforms

2,000 patent families in our portfolio

CEA-Liten, member of Carnot Énergies du Futur

CEA-Liten will receive €6 million in funding from Carnot Energies du Futur, the third-largest institute in the Carnot Network. The funds will be used to move early-stage innovations closer to industrial deployment by our partners and feed CEA-Liten's pipeline. Half of the funding is earmarked for fifteen exploratory research projects. These ambitious projects, which will kick off in 2024, will be led by post-doctoral students. Cooperation between Carnot Network members (ARTS, M.I.N.E.S., CEA-Leti, and Icéel) will also be a priority. Funding has also been granted to an additional four strategic projects addressing several of CEA-Liten's cross-disciplinary research areas. These major projects will produce significant results demonstrating scientific and technological capabilities likely to be of interest to industrial companies. ■

INSTITUT CARNOT Energies du Futur

CEA-Liten spearheading several French government research initiatives

One of the objectives of the French government's "France 2030" investment plan is to bolster the country's R&D capabilities in strategic sectors. CEA-Liten is co-heading several of these industry-specific programs with the French National Center for Scientific Research (CNRS). Three of the programs involving CEA-Liten started in 2023: one on batteries, one on advanced technologies for energy systems, and one on decarbonized hydrogen, which includes a high-temperature electrolysis project (CELCER-EHT) led by CEA-Liten.

The battery program focuses on new characterization and simulation tools and innovative battery chemistries and the associated BMSs. The decarbonized hydrogen program covers production, transportation, storage, conversion, and use cases. The program on advanced technologies for energy systems addresses solar energy and energy grids. This program will also help support a sustainable energy transition by integrating social sciences and humanities research conducted at Université Grenoble-Alpes. ■

FRANCE 2030

The CEA·Liten Journal

CEA-Liten partners in the news

Photo: © S. Perolari-REA-Le monde

2023, THE YEAR OF THE GIGAFACTORY

Gigafactories were all over the news in 2023, and CEA-Liten is proud to support its partners' solar, hydrogen, and battery gigafactory projects. These successful alliances are evidence of how CEA-Liten is putting its know-how to work for its partners. Read on to discover some of the gigafactory announcements that made 2023 a particularly successful year.

Enel invests in solar panel manufacturing to secure independence from China

Italian energy giant Enel is investing massively in a fifteen-fold increase in its Catania, Sicily solar panel plant's capabilities. The plant, operated by Enel company 3Sun, is expected to push its current annual production of 200 megawatts to 3 gigawatts by mid-2024. According to Enel, it will then be "Europe's largest solar panel plant."

February 6, 2023 - Agence France Presse

Europe goes head-to-head with the US on hydrogen with Symbio gigafactory

The ribbon was cut on Europe's largest hydrogen fuel cell gigafactory on Tuesday [December 5]. The plant, located in St. Fons, near Lyon, France, is operated by Symbio, a joint venture between Stellantis, Forvia, and Michelin. In terms of volume, the company has set a target of 50,000 systems by 2026. Initially the fuel cells will equip Stellantis utility vehicles and buses in Europe. Symbio will then address the pickup truck market in the US, where competition is especially fierce.

December 5, 2023 - La Tribune

Stellantis and Orano announce plans to create joint venture around disruptive battery recycling technology

On Tuesday, October 24, 2023, Stellantis and Orano announced their plans to create a joint venture on battery recycling. The new venture will pre-treat batteries to produce black mass, a powder containing critical metals, which will then be processed at Orano's planned hydrometallurgical plant in Dunkirk in northern France

October 24, 2023 - L'usine nouvelle

Ribbon cut on Genvia pilot line at former Camerone plant, paving the way for future gigafactory

Genvia cut the ribbon on its pilot line at the former Camerone plant in Béziers in the south of France at a ceremony held on Thursday, June 8. The company will manufacture high-temperature electrolyzers that produce green hydrogen. Genvia is a prime example of how the French government's France 2030 investment plan is helping build a domestic hydrogen industry.

June 8, 2023 - Midi Libre

France's first automotive battery gigafactory launches production

The ribbon was cut on Tuesday [May 30, 2023] on an automotive battery plant in the north of France operated by Automotive Cells Company, a joint venture between Stellantis, TotalEnergies, and Mercedes-Benz. It is the first gigafactory in France to volume-manufacture automotive battery cells and the first of three production units on the site, which is slated for completion by the end of 2024.

May 30, 2023 - Le Monde

Inocel to produce high-power fuel cells at new plant in Belfort, France

Grenoble-based startup Inocel has already secured letters of intent to purchase totaling €1 billion. At just 50 cm^3 and 100 kg, the company's new-generation low-temperature fuel cells are both compact and lightweight. And, with an impressive 300 kW (around 407 horsepower) output, they are also powerful. The innovation behind the product was developed over two years of research at CEA-Liten. Inocel plans to launch production in September 2024. ■

May 10, 2023 - Les Echos

Startups

Heliup

FUNDRAISING

Startup Heliup, which manufactures ultra-light solar panels, closed out a €10 million fundraising round. The company's innovation resides in the ultra-thin glass used to protect the solar cells. This, combined with an ultra-light mounting system, will make the solution ideal for metal-framed buildings that cannot support the weight of conventional solar panel systems. The innovation is protected by two CEA patents. This successful first fundraising round, which includes €4.5 million in equity, will position Heliup to begin commercializing its products and build its pilot manufacturing line in Le Bourget du Lac, France. Heliup is partnering with ITE INES.2S to make improvements to its products. ■

DistrictLab

LAUNCH

Startup DistrictLab is ready to go with its urban heat network optimization software. DistrictLab's solution covers the design and operation phases and can help with a variety of objectives, from decarbonizing and lowering the operating temperature of existing networks to facilitating the massive integration of recovered and renewable energy, deploying new systems, and developing innovative architectures. DistrictLab distills more than a decade of CEA-Liten R&D on complex energy networks in a software application that has a bright future ahead of it. ■

SEED-Energy

BUYOUT

Startup SEED Energy was created in 2017 to deploy a solution developed at CEA-Liten to analyze the profitability of multi-energy, multi-technology systems. Technip Energies, a leader in engineering and technology for the energy transition, acquired the startup on June 7, 2023. The startup's successful exit confirms the value its energy systems modeling capabilities bring to the industrial market. ■

INOOCQ

TECHNOLOGICAL BREAKTHROUGH

Inoocq is bringing a major technological breakthrough in product traceability to the cosmetics industry. The startup's solution, which took a decade of R&D to perfect, is now ready for the market. An invisible bio-compatible tracker, which is detected by a simple smartphone app, is integrated either into the product itself or its packaging. The accessible and easy to use system will be a powerful addition to the beauty market's anti-counterfeiting arsenal. ■

Solreed

PARTNERSHIP AGREEMENT

Solreed, a nascent CEA-Liten spinoff specializing in the reuse of old solar modules, recently signed a partnership agreement with a key solar panel market player. The partnership will position Solreed to bring its solution to the market and ramp up its operations quickly. The company will address environmental issues, of course. But it will also have a positive impact on society, with the ambitious objective of hiring only people who have been excluded from the job market. ■

01

Solar PV

The global solar energy market is growing rapidly, with production expected to reach nearly 1 TW by 2030. CEA-Liten is committed to supporting the expansion of solar in this fast-paced environment by conducting R&D spanning the entire value chain from materials to systems. With broad, deep know-how and excellent results scaling up new technologies, CEA-Liten is known in Europe as a leading center for solar energy research at the international state of the art.
CEA-Liten's solar energy research addresses high-efficiency, environmentally-sustainable PV cells and optimized systems, high voltage solutions, and troubleshooting algorithms for PV power plants. In terms of technologies, CEA-Liten innovates in heterojunction, TOPCon, and silicon-perovskite tandem cells. Here, the goal is to push efficiencies beyond 30%.
Sustainability is another pillar of CEA-Liten's solar R&D. Recyclability is of particular interest, with a focus on modular, easy-to-disassemble solar panel designs to facilitate the recovery and recycling of materials. CEA-Liten's proven lifecycle assessment (LCA) methods inform the choice of materials and facilitate the use of sustainable alternatives whenever possible.
In terms of use cases, CEA-Liten's research addresses everything from massive electricity production either by large photovoltaic power plants or by the deployment of new kinds of solar panels on surfaces that are already man-made to land transportation and mobility and self-powering space vessels.
Higher yields and new use cases will support the energy transition and create economic opportunity. All of CEA-Liten's advances in photovoltaic solar energy contribute to a more energy-efficient and environmentally sustainable future.

“CEA-Liten's advances contribute to a more energy-efficient and environmentally sustainable future.”

Interview with

David Duca

head of CEA-Liten's Solar Technology Division

01.

Where were you before you came to CEA-Liten? What brought you here?

I have 25 years of experience in the optics and semiconductor industries, in both R&D and manufacturing. Most of my career has been in France at STMicroelectronics, where I worked on the Crolles 2 Alliance program, and also at Sofradir. I also spent several years in Quebec, at Excelitas Technologies, where I was in charge of ramping up their manufacturing activities as director of operations at the site. I am thrilled to be at CEA-Liten, where I can put my experience to good use advancing solar photovoltaic energy—where photons and electrons meet—and the energy transition.

02.

What are some of the main challenges facing PV in France and how does CEA-Liten intend to address them?

I believe that the main strategic challenge—vertical integration—is at the European level. We need to ensure that every link in the domestic value chain, from polysilicon to module, is strong. CEA-Liten has a long, strong track record spanning materials, crystal growth, and wafer machining.

We are continuing to upgrade and improve our LabFab, where we are working on heterojunction, TOPCon, and other future generations of cells. The purpose of this remarkable R&D infrastructure is to get optimized, reproducible processes ready to transfer to our partners' pilot manufacturing lines in France and across Europe. We maintain a sharp focus on our fundamentals so that we can effectively optimize every process and subprocess involved in manufacturing today's solar technologies.

One of our priorities is to remain closely aligned with industrial realities like cell surface area and process throughputs at each step. Another is the future generation of tandem cells, which is expected to push efficiencies beyond 30%.

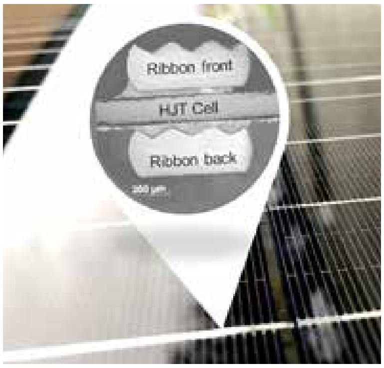
In terms of use cases, we need to keep covering surfaces that are already man-made with solar panels and look at addressing three-dimensional surfaces. Grid integration is also a challenge. We are working on increasing voltages and switching to direct current to reduce electrical losses and increase renewable energy penetration rates.

Finally, sustainability is also part of our strategy. This includes reducing the amount of raw materials that go into our technologies and designing modules that can be dismantled at the end of their useful life so that the materials can be recycled. And we are also addressing societal issues, like the public's acceptance of the technologies we develop. ■

Towards new-generation solar panels: innovations and prospects

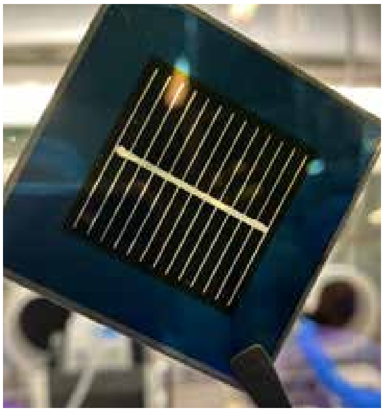
3 Highlights

We also developed new processes on the heterojunction pilot line at our LabFab. Our people adapted and qualification tested larger-format silicon wafers (with 80% more surface than M2 and G12 wafers) to support our partner Enel Green Power's 3Sun gigafactory start. We also found that a p-type crystalline silicon absorber was both thinner and more robust to environmental irradiation outside the atmosphere than n-type silicon, effectively demonstrating that heterojunction technology can be deployed in space. ■



If we are to mass-produce solar panels, we absolutely must reduce the amount of critical materials they contain. In 2023 we investigated a combination of nanocrystalline silicon thin films and ultra-thin indium oxide and silicon nitride layers, resulting in a 90% reduction in the amount of indium in the front face of the cells. We also successfully screen printed new metallization pastes, reducing the usual silver content by 40% to 60%. A 1:1 demonstrator module with a silver content of less than 25 mg per watt was produced. Leading manufacturers are currently at more than 35 mg per watt. ■

The PIN cells we developed with Enel Green Power subsidiary 3Sun achieved record efficiencies of 28.4% for a 9 cm² cell with shading correction. Most of the efficiency records in the literature are for cells measuring 1 cm², which makes this demonstration all the more impressive. ■



Bringing eco-design to solar power plants

The CEA developed a new impact assessment for solar photovoltaic power plants called EcoSPV. Leveraging an up-to-the-minute database, EcoSPV produces accurate results for indicators like the energy payback period and the carbon payback period. The initial release of the software covers the main system components that are deemed to have the greatest environmental impacts. Here, we are talking about inverters, transformers, PV modules, and electrical cables. It works by modeling both the power plant being assessed and a benchmark power plant based on typical data derived from a model of a real-world plant. EcoSPV is the latest addition to the suite of Life Cycle Assessment (LCA) tools developed under the INES.2S Institute for the Energy Transition initiative. ■

Shaping the future of agrivoltaics

The CEA is engaged in a national agrivoltaics cluster coordinated by France's Food, Farming, and Environment Agency (INRAE). The cluster, which spans research, innovation, and education, involves stakeholders from the public and private sectors. The goal is to support the reasoned development of solar photovoltaic energy generation on agricultural land. A law on agrivoltaics was passed by the French Senate in February 2023. The cluster's overriding objective is to create knowledge that will allow farms to maintain or increase yields and produce electricity. Solar panels can be beneficial to crops and livestock by modulating sun exposure and providing protection from hail, frost, and excessive heat. CEA-Liten's experts are mainly focused on the solar energy technology aspects of agrivoltaic installations. ■

CEA scientists in the spotlight at EU-PVSEC 2023

Several CEA scientists were honored at the 40th edition of EU PVSEC, the leading global photovoltaic solar energy conference and exhibition. Nouha Gazbour gave a talk on sustainability for the photovoltaic solar industry, and two CEA contributions (see below) won awards at the poster session.

* **1/** *IWyttenbach, J., Matheron, M., & Dupré, O. (2023). Ohmic shunt imaging in tandem solar cells. Poster presented at the 2023 European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC). .*

2/ *Allegre, J., Tsoulka, P., Manceau, M., Champault, L., Lemaitre, N., & Berson, S. (2023). Optimization of Wide and Narrow Bandgap Absorbers for All-Perovskite Tandem Solar Cells. Poster presented at the 2023 European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC).*

A closer look

Ohmic shunt imaging in tandem solar cells

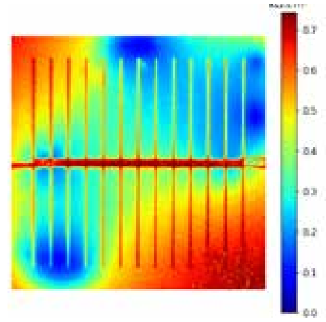


Figure 1: *Simplified modeling at V2T = 0.7 V.*

BACKGROUND

The conversion efficiencies of silicon-perovskite tandem photovoltaic cells are potentially much higher than commercially available cells. And the increased performance comes at a reasonable additional cost. Two-dimensional images of the multiple internal reactions at work inside the cells can be used to improve both stability and efficiency. This research introduced a new luminescence-based method for quantitatively imaging a particularly penalizing defect [1]: the ohmic shunt in the perovskite cell.

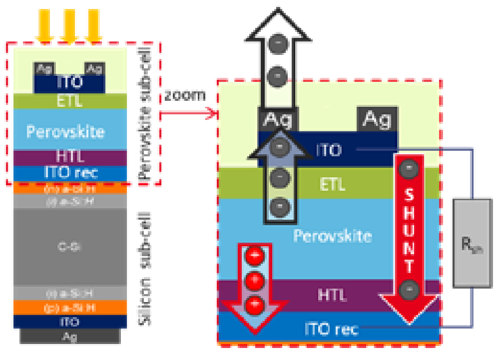


Figure 2: *Location and effect of the ohmic shunt in the top cell.*

METHODOLOGY & RESULTS

Silicon-perovskite tandem solar cells are a fairly recent development, so characterization data is still scarce. Selective, quantitative, non-destructive imaging methods like the one proposed here could effectively help isolate different defects within the cells, determine their specific impacts, and make targeted improvements. The idea for the method came from the chance observation of variations in the luminescence profile as a function of the supply voltage to a cell. In a second experiment, the supply voltage turned out to sequentially trigger the illumination of sub-cells. These observations were then generalized via a theoretical study in which contextual simplifications to the equivalent electrical model were determined. For example, at around 0.7 V, luminescence originates solely from the silicon; the current-voltage curve slope depends solely on the perovskite cell shunt. Luminescence/current calibration is then used to map ohmic shunt for each pixel [2]. Measurements taken on more than 60 cells revealed a close correlation between the images and the electrical measurement of the shunt. A specific experiment was then conducted to establish the link between the shunt and the thickness of the perovskite. Local shunt shapes, locations, and strengths can be used to pinpoint potential improvements related to manufacturing, encapsulation, or aging.

CONCLUSION

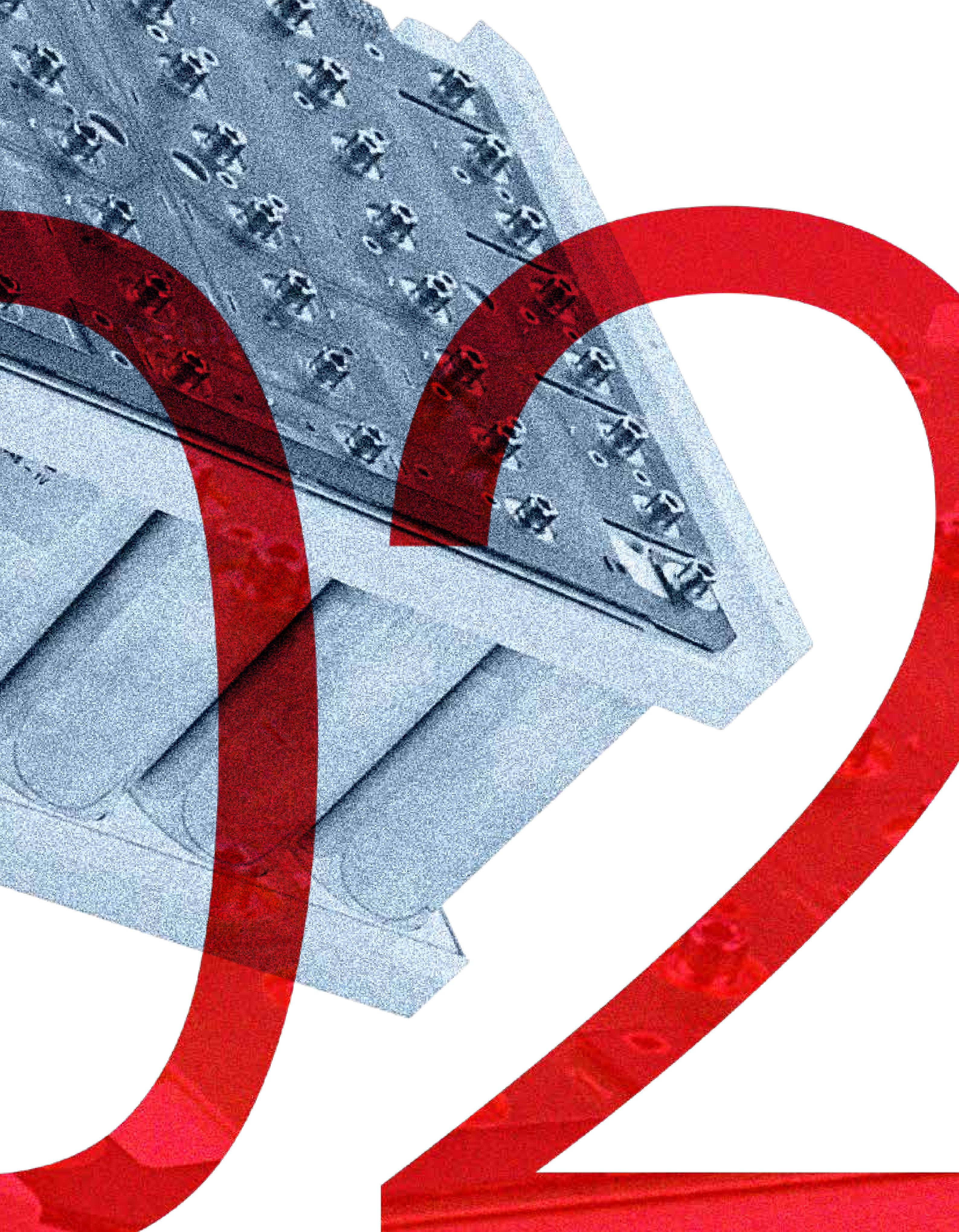
This new method leverages luminescence measurements to selectively map the ohmic shunt of tandem solar cells. Due to moderate positive voltage and absence of heat, radiation, or a specific atmosphere, this is a non-destructive test. The measurement conditions make modeling simpler, and the shunt is calculated by differential resolution [3]. The non-destructive application of this method to other parameters will make it possible to map multiple defects.

LEARN MORE

[1] *C. M. Proctor et T.-Q. Nguyen, "Effect of leakage current and shunt resistance on the light intensity dependence of organic solar cells", Appl. Phys. Lett., vol. 106, 8, p. 083301, Feb. 2015, doi: 10.1063/1.4913589.*

[2] *D. Hinken, K. Ramspeck, K. Bothe, B. Fischer, et R. Brendel, "Series resistance imaging of solar cells by voltage dependent electroluminescence", Appl. Phys. Lett., vol. 91, 18, p. 182104, Oct. 2007, doi: 10.1063/1.2804562.*

[3] *M. Seeland, C. Kästner, et H. Hoppe, "Quantitative evaluation of inhomogeneous device operation in thin film solar cells by luminescence imaging", Appl. Phys. Lett., vol. 107, 7, p. 073302, Aug. 2015, doi: 10.1063/1.4929343.*


02

Batteries

For clean mobility to take hold, new battery technologies will be needed. CEA-Liten conducts research to improve battery performance and develop new generations of battery chemistries. The reduction of critical materials—an overriding theme in all our battery research—is a necessary condition for mass-market battery deployment. We pursue research avenues and focus on innovations with a capacity to improve energy and power density, extend product lifespans, enhance safety, lower total cost of ownership, and reduce environmental impacts.
Our holistic approach to energy systems positions us to make unique contributions to decarbonizing mobility and increasing grid flexibility. We also possess deep knowledge of the entire battery value chain, from materials to systems to recycling. This is a key pillar of our strategy.
Two of our priorities are new generations of batteries with higher energy densities beyond the NMC-graphite system and with lower environmental impacts beyond the LFP-graphite system. We are working to overcome the technological hurdles to optimizing these systems. Our goal is to reach a tradeoff between the characteristics expected of these products that will be compatible with mass market deployment.
The kinds of system optimizations needed to support the widespread electrification of transportation will depend on advances in battery chemistry, one of CEA-Liten's long-standing areas of expertise. Our objective is to select the best battery cell chemistries and form factors. We also address the relevant mechanical, electrical, and thermal constraints in the integration scenarios we recommend.
We have formed partnerships with companies like Solvay Umicore, Saft, ACC, Orano, and Stellantis to support this research.

"We make unique contributions to decarbonizing mobility and increasing grid flexibility"

New milestone on path to tomorrow's batteries

CEA-Liten reached a milestone in its new-generation all-solid-state battery research in 2023, with an initial prototype of around 1 Ah with an all-solid sulfide electrolyte. The material is widely accepted by the scientific community as one of the frontrunners in the race to bring all-solid-state batteries to the market. Here, it was combined with a layered NMC-type material at the positive electrode and silicon at the negative electrode. To scale up from low-capacity lab cells (in the tens of mAh) to this 1 Ah prototype, all manufacturing processes were optimized. ■

First-ever hybrid polymer membrane produced by reactive extrusion

Solgain™ is a hybrid polymer electrolyte technology developed by Solvay and the CEA in which the electrolyte is encapsulated in the electrodes and membrane during manufacturing. The partners tested a novel alternative process using reactive extrusion (REX) to eliminate the membrane coating step, which requires a sacrificial solvent. The extruded membrane was tested in a button battery between two Solgain™ electrodes. It performed as well as conventionally-manufactured membranes during cycling. ■

Extrusion process reduces toxic solvent use

Currently, the positive electrodes in Li-ion batteries are manufactured using a coating process that involves toxic organic solvents. There is a more environmentally-friendly water-based process, but it can only be used to manufacture negative electrodes. CEA-Liten successfully tested an alternative extrusion-based manufacturing process for the positive electrode that does not require the use of toxic solvents and saves on water. The mechanical characteristics and electrochemical performance of the experimental electrodes were promising. The formulation and process were further improved to enable continuous extrusion with a single drying step without negatively impacting performance. ■

A closer look

Major advances bring all-solid-state Li-ion batteries closer

BACKGROUND

The automotive industry is counting on the scientific community to drive advances in batteries. The goal? Continuous improvements in battery safety, performance, and sustainability. One promising avenue is the all-solid-state technology. These batteries eliminate the need for liquid electrolytes and the associated safety risks.

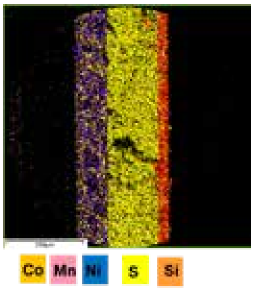


Figure 1: *Electron microscope cross section of the battery with the positive electrode (Co, Mn, Ni), the negative electrode (Si), and the electrolyte (S).*

METHODOLOGY & RESULTS

Researchers from CEA-Liten and CEA-Irig worked together to develop innovative all-solid-state battery prototypes. Solid inorganic sulfide electrolytes were used in the battery cells. These solid electrolytes demonstrate ionic conductivity at room temperature similar to that of liquid electrolytes. Commercially -available layered NMC oxides were selected as the active materials at the positive electrode; silicon nanoparticles were used at the negative electrode (Figure 1). These materials will ultimately enable the production of lithium-metal-free high-energy all-solid-state cells. Lithium metal, with its exceptional energy density, was an early candidate as the active material for the negative electrode in all-solid-state batteries. However, cycling issues prevent its practical application.

The electrode coating process was adapted from conventional Gen3 processes for this technology. This process enabled the scale up from lab-scale cells (1 mAh to 2 mAh) to flexible pouch cells (10 mAh to 20 mAh) with no decrease in performance. In all-solid-state batteries, high pressure on the cells must be maintained during cycling. The scaled-up cells considerably reduced the operating pressure from 100 MPa or more at laboratory scale to just 1 MPa (Figure 2) [1,2]. The cells' electrochemical performance did not decrease at the much lower pressure, a significant finding that was published in the *Journal of Power Sources* [3].

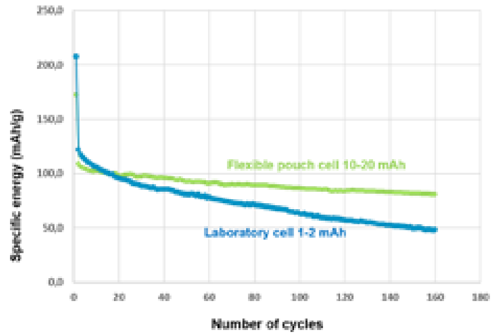


Figure 2: *Performance comparison of a laboratory cell (blue) operating at a pressure of 100 MPa and a pouch cell (green) at a pressure of 1 MPa.*

CONCLUSION

Substantial additional research will be needed to bring the technology to a higher readiness level and transfer it to a manufacturer. Looking ahead, we will investigate the mechanisms that make low-pressure operation possible to make further improvements in performance and ultimately, meet automotive requirements. This PhD research project was financed in part by the CEA FOCUS-Batteries program.

LEARN MORE

[1] *D.H.S. Tan et al., "Carbon-Free High-Loading Silicon Anodes Enabled by Sulfide Solid Electrolytes", Science, 373 (2021) 1494-1499. doi: 10.1126/science.abg7217*

[2] *D.H. Kim et al. "Sheet-Type Li6PS5Cl-Infiltrated Si Anodes Fabricated by Solution Process for All-Solid-State Lithium-Ion Batteries", J. Power Sources 426 (2019), 143-150. Doi: 10.1016/j.jpowsour.2019.04.028*

[3] *M. Grandjean et al, "Low pressure cycling of solid state Li-ion pouch cells based on NMC - Sulfide - nanosilicon chemistry", J. Power Sources (2023), 233646, 10.1016/j.jpowsour.2023.233646*

New, more sustainable battery materials

In the best-performing Li-ion batteries currently available, the negative electrode is made from graphite and the positive electrode is made from NMC (nickel manganese cobalt). The problem with NMC is that nickel and cobalt are in short supply.

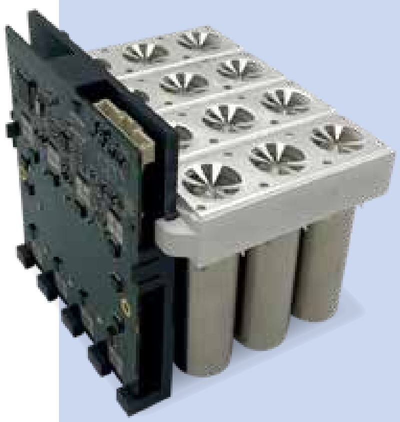
Assessing the environmental impacts of the technologies we develop is an integral part of our research at CEA-Liten. We have been investigating new kinds of positive electrode materials for the past several years. Our goal is to find materials for Li-ion and beyond-Li-ion battery technologies (like Na-ion and K-ion) that do not contain critical metals. The electrochemical performance of several of the materials we are studying looks promising. Very high capacities of around 300 mAh.g^{-1} and a specific energy of 900 Wh.kg^{-1} were obtained in button batteries using low-cost lithiated manganese oxides with a disordered rocksalt (NaCl) structure. Plus, the materials' carbon footprint is half that of NMC. The next steps will be to optimize the coating process and test the materials in pouch cells.

Prussian white ($K_2Mn[Fe(CN)_6]$) has a theoretical energy density of around 600 Wh/kg in K-ion systems and is compatible with an aqueous, toxic-solvent-free coating process. An energy density of 450 Wh/kg has already been demonstrated on materials synthesized in the lab, and there is still room for further improvement.

Over the past decade, CEA researchers have also synthesized several families of all-organic materials (without transition metals) in aqueous form and tested them. Of these materials, significant research has been done on organic battery prototypes (180 mAh) using lithiated terephthalates. Assembled in a Li-ion configuration, these batteries offer a promising energy density of 60 Wh/kg and, crucially, an operating voltage close to that of traditional Li-ion batteries. ■

Environmental impact assessment according to battery design

Li-ion batteries are highly variable, which makes it difficult to assess their environmental impacts. Battery life, a key parameter in a battery's overall environmental impact, is often determined arbitrarily in impact assessments. CEA-Liten developed a new battery lifecycle assessment (LCA) method with an integrated aging model. The goal is to predict a battery's service life based on its design. The easy-to-configure assessment, intended for use in eco-design processes, has the potential to reveal improvements that could reduce environmental impacts from the early stages of the battery design process. ■



An innovation that makes battery modules more repairable

Sustainable electric mobility will require solutions for limiting the environmental impacts of battery systems from the early stages of the design process. Repairability is just one of the battery sustainability challenges CEA-Liten is actively addressing with a repairable battery module whose flexible connectors make it easy to replace faulty cells. Even better, all of the battery's mechanical and electronic parts can be reused at the end of the battery's service life or after the replacement of a faulty cell. Validation testing of the module's mechanical and electrical architecture has been completed in the lab. ■

Regulations for a sustainable battery industry in Europe

The European Commission Joint Research Centre published a draft of its low-carbon battery manufacturing regulation in the summer of 2023. Experts from the CEA and BRGM (France's national geology and mining research institute) provided recommendations on the proposed methodology. Read their recommendations here. ■

A boiling fluid to fight thermal runaway in batteries

The temperature inside electric vehicle batteries must be carefully controlled to avoid thermal runaway, a major safety hazard, and to maximize service life. Developing an effective thermal management solution is vital. CEA-Liten tested a solution conventionally used in data centers on batteries: the direct cooling of components using a dielectric fluid. The concept is simple: In the event of local overheating, the fluid boils. We developed a two-phase loop to test the effects of confined boiling at the scale of a mini-channel between two cells. A numerical analysis was carried out in parallel and compared to the experimental data, confirming the cooling system's potential to effectively dissipate heat. ■

Silica aerogel halts thermal runaway in batteries

Enersens manufactures silica aerogel strips with exceptional thermal insulation properties. In research conducted for an EasyPOC project, the CEA analyzed the strips' capacity to halt the propagation of thermal runaway in automotive-grade Li-ion battery cells. The purpose of the research was to obtain detailed measurements of the mechanisms at work during abuse testing. The strips were characterized by thickness and submitted to compression simulating the pressure sustained when battery cells swell. The data obtained was used to further improve implementation of the strips. Enersens now has a deeper understanding of how its products behave in the complex conditions of thermal runaway and can offer its customers better-performing solutions. ■

New methods for faster lithium-ion battery analysis

Every year, CEA-Liten and CEA-Irig conduct a number of battery-related experiments on the large scientific instruments at nearby ESRF and ILL. These experiments generate huge numbers of images. Early-career researcher Victor Vanpeene is tackling the complex problem of how to store, access, and extract useful data from these images. He won a Science Impulse fellowship to carry out his massive data management project.

Smart, automated data management

The overall objective of this far-reaching project is to design a solution to save, classify, archive, and retrieve the images acquired on the large instruments. The idea is for all scientists to be able to access the images via a shared database. Smart, automated tools will have to be developed so that the massive amounts of data acquired on different battery chemistries can be analyzed more rapidly.

Where multiple characterization projects come together

The Grenoble Battery Hub, a joint initiative of ESRF, ILL, and the CEA designed to facilitate access to the large instruments for battery-related research, will benefit directly from the improved data management system. The Battery Hub's multidisciplinary investigations address all aspects of batteries. Post-mortems, abuse tests, extremely advanced electrochemical characterization, and scatter and other tomography techniques produce a wealth of information. According to Vanpeene, "Over the past three years, more than 15 terabytes of tomography data have been produced, and we are anticipating the amount of data produced to grow by an additional 3 terabytes per year. For all that data to be useful, we have to be able to work with it, to extract information from it." ■

03

Hydrogen and sustainable chemicals and fuels

CEA-Liten is investigating hydrogen and carbon-containing substances as potential solutions for decarbonizing a variety of use cases, storing energy, and making the energy mix more flexible. Our research addresses the production, storage, transportation, and conversion of hydrogen into electricity and heat. We are also exploring the production of carbon-containing substances of interest for industry and transportation, either through the transformation of carbon and bioresources or the use of hydrogen and energy.

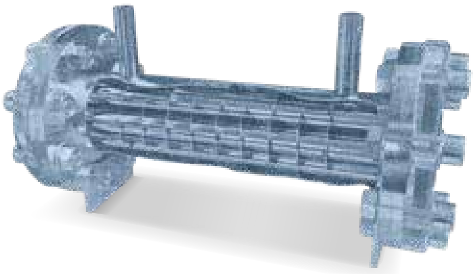
Efficiency, cost control, and sustainability are key factors in how we choose the technologies we develop. We are investigating high-temperature solid-oxide electrolysis (SOEL), a technology that has the potential to produce hydrogen efficiently and cost effectively, and anion exchange membrane electrolysis (AEMEL), another high-performance technology.

Our energy-conversion technology of choice is the low-temperature, compact, high-performance proton exchange membrane fuel cell (PEMFC). In terms of transportation and storage, we are studying liquid organic hydrogen carriers (LOHCs).

The focus of our carbon-related research is how to use hydrogen and nuclear or renewable energy to produce carbon-containing substances like methane, methanol, and kerosene for energy, chemicals, and long-distance transportation.

Our in-depth knowledge of modeling, of the interactions between hydrogen and materials, and of the safety issues around hydrogen informs this research.

We also use performance data gathered on our own test benches to assess the potential of new innovations and analyze what their integration into the global energy landscape would look like. Companies like Genvia (hydrogen production), Symbio, Inocel, and Faurecia (fuel cells), and Khimod (methanation) are developing and commercializing these CEA-Liten technologies.



> **“Efficiency, cost control, and sustainability are key factors in how we choose the technologies we develop”**

Getting ceramic cells with anionic conductivity to last longer

The purpose of the CELCER-EHT high-temperature electrolyzer project is to develop innovative materials and processes for semi-industrial-scale (200 cm^2) high-temperature steam electrolysis (HTSE) cells with improved performance and longer lifespans than the current state of the art. The project, financed through a national hydrogen program (PEPR H2), includes eleven research institutions, including the CEA. So far, the project has focused on multilayer structures with internal microstructures featuring a gradient of particle sizes and porosities for optimized electrodes. This early research produced a first-generation cell that operated for nearly six months (more than 4,000 hours) with degradation of less than 1% per 1,000 hours. Currently, innovative materials for the oxygen electrode are being investigated with the goal of integrating them into a future generation of cell. ■

Record

1 ton of hydrogen

produced by a single HTE stack

Modeling for high-temperature electrolysis

As high-temperature electrolysis (HTE) gains in maturity, our research is focusing on the integration of HTE stacks into high-power industrial systems. With the technology moving closer to market deployment, modeling is becoming an important tool for more accurately dimensioning these systems and selecting the most appropriate architectures. For example, we built a 3D model of a unit stack (of 200 cm^2 cells) integrating thermal, fluidic, and electrochemical effects to generate new insights into the temperature ranges inside the stack at different operating points—the kind of information that will ultimately lead to optimized management strategies. ■

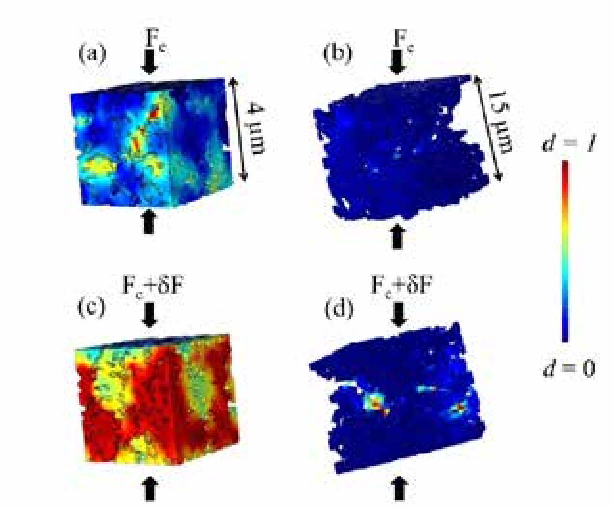
New insights into what makes solid-oxide electrolyzer cells mechanically robust

BACKGROUND

High-temperature steam electrolysis (HTSE) converts electricity from renewable sources or nuclear power plants into hydrogen. At the center of the technology: the solid-oxide electrolyzer cell, or SOEC, made up of a dense ceramic electrolyte sandwiched between two porous ceramic electrodes. The imbalance between the thermal expansion coefficients of the alternating layers of materials in the stack induces thermomechanical stress in the system, substantially lowering performance.

METHODOLOGY & RESULTS

More mechanically robust SOECs are vital to longer HTE lifespans. Predicting the onset and propagation of cracks in the electrodes is necessary but also challenging, mainly because the porous ceramic material's complex 3D microstructures make it particularly difficult to analyze. A PhD student cosupervised by CEA-Liten and engineering school INSA Lyon addressed this issue. Models were used to identify areas in the microstructures likely to be responsible for the onset and propagation of cracks [1]. Next, very specific experimental data had to be gathered to confirm the models' validity. The materials were then characterized at a scale in the tens of microns, representative of the electrode layers, using micro-mechanical testing techniques. Micropillars were fabricated on a focused ion beam machine at CEA-Leti and then tested at INSA in Lyon. A mechanical property called compressive yield strength was determined for materials with different porosities. The validity of the theoretical model was confirmed by the tests, which also delivered new insights into the mechanisms that underpin electrode degradation. The ceramic tested in this research turned out to be prone to localized damage at low porosities, and more diffuse damage at high porosities. Numerous stable microcracks were observed in the more porous material [2].



Visualization of the cracks created in porous microstructures submitted to compression: First microcracks created in the microstructure for a porosity of a) 33% and b) 63%. Evolution of the damage variable after a small increment of charge at c) 33% and d) 63%.

CONCLUSION

This powerful digital model will be used in CEA-Liten research on the mechanical robustness of solid oxide electrolyzer cells. Specifically, it will help to better predict electrode degradation and improve HTE system operation over time.

LEARN MORE

[1] *A. Abaza, J. Laurencin, A. Nakajo, S. Meille, J. Debayle, D. Leguillon, "Prediction of crack nucleation and propagation in porous ceramics using the phase-field approach", Theoretical and Applied Fracture Mechanics, 119, 2022, 103349*

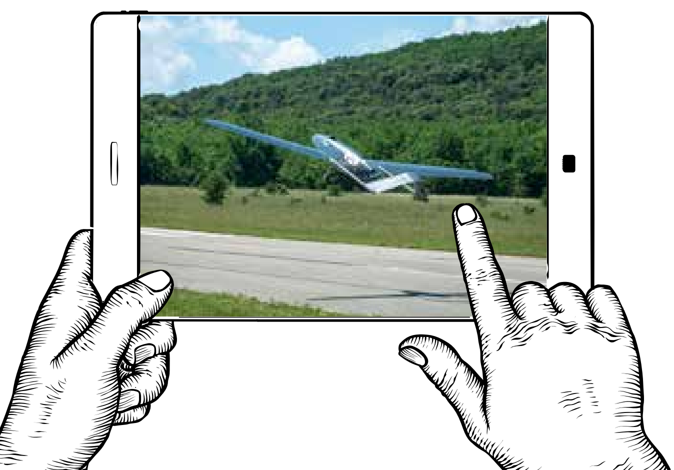
[2] *A. Abaza, J. Laurencin, A. Nakajo, M. Hubert, T. David, F. Monaco, C. Lenser, S. Meille, "Fracture properties of porous yttria-stabilized zirconia under micro-compression testing", Journal of the European Ceramic Society, 42, 2022, 1656-1669*

Recycled platinum fuel cells

Recycling critical raw materials from end-of-life PEFMCs and SOFCs is the focus of the European Best4Hy project. Recycling platinum from PEMFCs will be just one of the topics addressed. The idea is to create a closed loop in which the recycled materials are reused in the manufacturing of new PEMFC and SOFC components. Different catalyst synthesis processes using Pt salts were investigated and the most promising one scaled up. The recycled catalysts produced were tested in catalytic inks and, later, in MEAs with different surface areas. The catalytic ink formulation was fine-tuned and a MEA with a 100% recycled catalyst was produced and tested in a single cell in conditions representative of an industrially-manufactured stack in operation. Compared to a MEA made with commercially-available components, the test MEA performed at 96% at 1 A/cm², well above the target performance of 80%. ■

Hydrogen drone

Watch the test flight of the hydrogen drone developed by the CEA, Centre de Recherche de l'École de l'air et de l'espace, and Atechsys.



Better automotive PEMFCs

PEMFCs are not yet mature enough to meet the automotive industry's volume manufacturing requirements. CEA-Liten is coordinating the European DOLPHIN project, which was created to assess several innovative component manufacturing technologies. So far, processes to make the gas channels and current collector grooves smaller have been developed. Large-surface (170 cm²) active layers were produced using a catalytic ink coating process. The electrochemical performance obtained was similar to that of the leading commercial product. Mini-stacks with six cells were tested in conditions representative of an automotive use case. The value of these innovations was confirmed by the excellent performance obtained during testing: 1.5 W/cm² to 2 W/cm² at 0.66 V plus significantly improved kW/l and kW/kg compared to the known state of the art. The next step will be to build and test a 5-kW demonstrator. ■

Modeling tools for safer hydrogen use

The CEA is committed to making hydrogen safer. While earlier investigations focused on the nuclear industry, today's developments are targeting the safety of hydrogen for the energy transition. Over the years, this research has produced a number of modeling tools. CEA-Liten and CEA-ISAS (the institute for applied sciences and simulation for low-carbon energy) joined forces to create a software suite leveraging these tools so that all CEA hydrogen safety research can benefit from them. The software will cover the dimensioning of the safety components used in hydrogen systems and equipment as well as safety distance calculations. A modular architecture will facilitate future upgrades to meet changing needs.

Europe supports the design of more environmentally-friendly hydrogen systems

The purpose of the European eGHOST project, launched in 2021, was to investigate PEMFC and SOFC systems from an ecodesign and sustainability perspective. In this research, environmental, societal, and economic impact indicators for hydrogen systems were developed based on a 48 kW fuel cell stack using data gathered by a partner company. The goal is to use the indicators to make sure that the PEMFC and SOFC systems developed, also within the scope of this project, are designed not only for safety, performance, quality, and cost, but—equally—for their impacts on the environment, society, and the economy. A set of eco-design guides are being written by the project partners for hydrogen industry stakeholders to help them make their systems more sustainable from the initial technology development stages.

Interview with

Muriel Matheron

Muriel Matheron, in charge of CEA-Liten's circular carbon economy activities

01.

What are "Power to X" and "Biomass to X"?

"Power to X", or "P2X", uses electricity produced from renewable sources, hydrogen, or nuclear and biogenic or atmospheric CO_2 to produce sustainable non-fossil-based substances. "Biomass to X", or "B2X", uses the compounds present in biomass as a source of carbon plus hydrogen to produce biofuels or other bio-based substances such as methane, methanol, liquid hydrocarbons, or olefins, for example. P2X and B2X address markets like long-distance air and maritime transportation, chemicals, and energy.

02.

What kind of research is CEA-Liten doing in these areas?

We are looking at catalytic hydrogenation processes as a path to developing optimized methanation reactors for the synthesis of carbon-containing substances. We are also bringing our in-depth knowledge of thermochemical processes to hydrothermal and dry biomass conversion. What we are trying to do is address an end-to-end conversion chain to maximize conversion yields and energy efficiency. Heterogeneous catalysis is another topic we are actively investigating and gaining more experience with. Specifically, we are trying to make the reactions more selective and increase yields. Our experience with thermoconversion is helping us explore the transformation of new carbon-containing resources. Last but not least, we can also take full advantage of CEA-Liten's hydrogen technologies and process optimization know-how, both of which are vital to maximizing system efficiencies.

03.

Can you share some of CEA-Liten's highlights from 2023?

We converted food waste into a biofuel in research for the European Waste2Road project. Hydrothermal liquefaction, a pressurized, water-based process that takes place at around 300 °C and 150 bar, was used to transform the raw material into an intermediate biocrude. The biocrude produced was then hydrotreated by a partner to obtain the desired biofuel. Both the process and the quality of the intermediate biocrude will have to be improved further. However, based on the initial results, this does appear to be a promising path toward the production of sustainable liquid fuels. We are preparing proposals for additional European projects to support our continued research on this technology. ■

The energy transition needs catalysts

Catalysts are materials that facilitate thermodynamically possible chemical or electrochemical reactions. These materials increase reaction kinetics and can be used selectively, making them valuable tools in the production of high-added-value substances. CEA-Liten's catalyst R&D, which spans the entire value chain, includes technical and economic analyses and lifecycle assessments. We begin by developing catalysts in the lab. The catalysts are then tested so that the best ones can be selected and scaled up for final testing in a reactor. Both *in situ* and *operando* characterization techniques are used to provide deep insights into the reaction mechanisms at work. This allows us to develop new catalysts faster. Further development work targets specific use cases in three main areas: the circular carbon economy, hydrogen production by high and low-temperature water electrolysis, and ammonia synthesis.

Co-based NaBH4 hydrolysis catalyst on a nickel foam for H2 generation.

In 2023, CEA-Liten synthesized and tested Na-FeMnOx catalysts for the hydrogenation reaction of CO_2 for the production of carbon-containing molecules (C5+, e-fuel) in research financed by the Carnot Network. The purpose of the research was to increase the CO_2 conversion rate and reaction selectivity. The molecules were doped with cobalt and copper, effectively improving the selectivity of the reaction for hydrocarbon production.

We also investigated the electrochemical reduction of CO_2 to CO, a key molecule in the synthesis of many carbon-containing substances. In response to our R&D partner's request, we developed a Pd-based catalyst and integrated it into a special electrolyzer that uses pure CO_2 to generate CO with a faradaic yield of 40%. A European project proposal to increase the surface area of the electrodes to 100 cm^2 and integrate them with the support of a partner manufacturer (TRL5) has been submitted. ■

Interview with

Jessica Thery

Manager for CEA-Liten at
the Nanocharacterization Platform (PFNC)

01.

What are some of the issues around characterization in energy-related R&D?

Characterization plays a crucial role in establishing relationships between the materials a device is made of and the device's performance. Ultimately, this information can be used to make improvements. There are a few issues specific to energy R&D. First, you have to gather data from representative areas of the materials and systems being characterized. This can be done by taking measurements at different scales or by using 3D techniques. *In situ* analyses can also help ensure that the data represent the mechanisms at work during system operation as faithfully as possible. Finally, experimental data and simulation can be used together to gain even deeper insights into these mechanisms. In-depth knowledge of numerical modeling and analysis tools and methods is the key to optimal data acquisition, analysis, and interpretation.

02.

What characterization capabilities does CEA-Liten have?

We have a team of around 20 people. The Nanocharacterization Platform, which we are fortunate to be able to use alongside CEA-Leti and CEA-Irig, is home to around 50 pieces of advanced equipment. The platform's policy is to acquire state-of-the-art equipment to meet the needs of our research. Recently, for example, the platform installed a laser on a focused ion beam microscope.

03.

What did you work on in 2023?

Working together with CEA-Irig at the Nanocharacterization Platform, we implemented methods at different scales to paint a more detailed picture of NdFeB magnets. The goal was to capture quantitative phase, grain size, and grain boundary information and cover light elements like boron, which require specific detectors. We are also using characterization to study the aging of high-temperature electrolyzers in stacks, recycled battery materials, the perovskite layers of tandem PV cells, and PEMFCs.

A closer look

Oxygen's role in the back-and-forth movement of lithium ions in batteries

BACKGROUND

Layered transition metal oxide electrodes are widely used in high-energy-density lithium-ion batteries. Alterations of the electrodes' structure and morphology during cycling lead to a decrease in performance. Innovative methods combining experimentation and simulation can help deepen our understanding of the phenomena at work. CEA researchers recently shed new light on the role of oxygen atoms during lithium deinsertion, proposing a new theoretical and methodological framework for research to identify new materials that exploit oxygen activity.

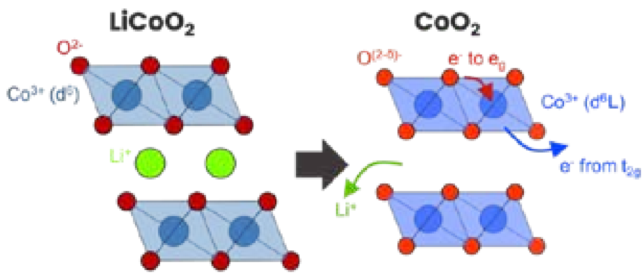


Figure 1: *Self-regulation of negative charge transfer between the oxygen "p" and cobalt "eg" orbitals during lithium ion deinsertion.*

METHODOLOGY & RESULTS

Layered transition metal oxides ($LiMO_2$, M:Ni, Co, Mn) are the materials of choice for positive electrodes due to their ability to reversibly intercalate lithium ions without altering the electrode's crystalline structure. $LiCoO_2$ is one of the most studied and used cathode materials [1]. However, the mechanism governing the redox process in relation to the electron distribution around oxygen and cobalt during lithium deinsertion is still not well understood. Original approaches combining experimental methods and *ab initio* simulations [2] were developed to gain insights into the role of oxygen and cobalt atoms in this process. Hard X-ray photoelectron spectroscopy (HAXPES) [3] and atomistic calculations revealed the role of oxygen orbitals in the self-regulation of charge around cobalt atoms during lithium deinsertion—a first. Coulomb repulsion between the cobalt orbitals (d) and the charge transfer between the cobalt and oxygen (p-d) along the deinsertion of lithium ions between the $LiCoO_2$ and CoO_2 phases [4] were measured to determine the role of cobalt and oxygen in the redox reaction.

Figure 1 shows the transfer of negative charge between the oxygen "p" and cobalt "eg" orbitals during lithium ion deinsertion. This research demonstrates the major role oxygen plays in redox in $LiMO_2$-type materials, especially those rich in lithium and nickel heralded for future generations of batteries.

CONCLUSION

This research produced major new insights into charge transfer in Li-ion batteries and significantly advanced our understanding of electrochemical processes at the interfaces between the electrode materials and electrolyte. These results will support the development of innovative solutions for stabilizing these interfaces in future generations of batteries.

LEARN MORE

[1] *A. Manthiram and J. B. Goodenough, Layered lithium cobalt oxide cathodes, Nat. Energy 6, 323 (2021).*

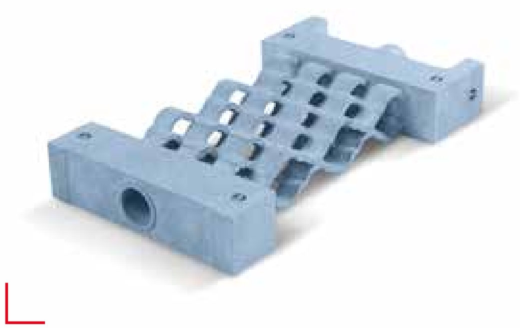
[2] *Roberto Fantin's PhD dissertation, part of the FOCUS-Batterie program. HAXPES measurements were performed at the Nanocharacterization Platform (PFNC).*

[3] *Roberto Fantin, Ambroise van Roekeghem, and Anass Benayad, Surf Interface Anal. 2022; 1-7.*

[4] *Roberto Fantin, Ambroise van Roekeghem, and Anass Benayad, PRX ENERGY 2, 043010 (2023).*

04

Materials and the circular economy



CEA-Liten brings a unique skillset to building a more environmentally sustainable and circular economy. We possess proven expertise in ecodesign, the characterization of materials, the manufacturing of parts with innovative designs, lifecycle analysis, processes with low environmental impacts, compatibility between materials and their environments, chemistry, recycling, and safe, sustainable development approaches. We have the capabilities to develop innovative processes to meet the needs of the companies and research labs we partner with, and our solutions are designed to make more efficient use of resources and improve sustainability.

One of the things that makes CEA-Liten unique is our ability to design parts with innovative designs and respond to the wide-ranging needs of partners in the automotive, nuclear energy, health, aerospace, and new energy technology industries. We also have the R&D facilities and expert staff needed to scale up the technologies we develop.

One of the throughlines of our research is the ability to challenge conventional processes to obtain new levels of performance from a material. We have earned a reputation as a center for expertise in the microstructural and mechanical characterization of materials and multi-material assemblies, additive manufacturing, printed electronics, brazing, and hot isostatic pressing (HIP).

Finally, we are investigating critical materials used in renewable energy systems like Li-ion batteries and materials such as polymers to create closed-loop recycling processes and improve these materials' environmental footprints. Aware of the need to save materials, we reuse rare and costly materials as much as possible and replace petrochemical products with bio-based and, in some cases, biodegradable, materials.

“Our goal is to develop innovative processes for more sustainable and efficient use of resources”

Orano and CEA partner on Li-ion battery recycling

EU legislation is expected to accelerate the uptake of electric vehicles by 2035, so the time to tackle the challenge of recycling end-of-life EV batteries is now. Energy company Orano has been working with the CEA on an innovative recycling process since 2019. The principle is to address all stages of recycling, from the safe disassembly of batteries to the production of new cathode materials. The research has won the financial backing of the EU Horizon Europe R&D and innovation framework program (through the Batraw and Respect projects), the French government (through the France 2030 plan), and from the Nouvelle-Aquitaine regional government.

Orano and the CEA plan to develop a legally compliant, environmentally sound, and financially profitable end-to-end recycling process. The first step is safely dismantling the battery modules without altering or losing any of the material. Materials of interest (especially the graphite and active cathode materials) are then separated and concentrated during a pre-treatment step. During the last step, materials may be chemically dissolved, residual impurities removed, and materials of interest extracted using hydrometallurgical techniques. The goal is to end up with precursors that can be reused in the production of new battery materials. Other materials, such as copper and aluminum, can also be recovered more efficiently using this process. As for the graphite in the anode, the partners are currently working on regenerating this material to a battery-grade standard.

The partners also investigated a different, "direct" recycling process in 2023. It involves regenerating cathode materials from scrap from gigafactory production lines or materials from end-of-life batteries. The active material is recovered as selectively as possible, and then any potentially disordered crystalline structures are reordered. This kind of approach calls for selective, non-destructive processes that are also compatible with deployment at an industrial scale. So far, the results have been positive. Heat treatment led to the recovery of 90% of the initial capacity of a Ni-rich NMC (nickel, manganese, cobalt) material from black mass from cycled battery cells. ■

Making printed electronics more sustainable

The benefits of printed electronic circuits—low-cost, large-area, and conformable—are now clear to stakeholders in the automotive and other industries. Now it is time to dig deeper into the environmental impacts associated with the technology. The EU is backing growing numbers of projects on alternatives to conventional petroleum-based polymers for printed electronics. These can include bio-based polymers, of course, or any other less-toxic and more environmentally-friendly material. Another important consideration to be addressed from the initial design stages of a new product is the end-of-life recovery and recycling of materials. With more than fifteen years of experience in printed electronics, CEA-Liten is a leader in the field. The institute is engaged in several EU projects to support the transition to more sustainable materials for printed electronics. What sets CEA-Liten apart is its expertise in polymers, recycling, and lifecycle assessments applied to printed electronics processes. ■

Plastics that are lighter on the environment

A total of 390.7 million tons of plastic were produced worldwide in 2021. This figure could skyrocket to 1.2 trillion tons per year by 2060. CEA-Liten, which has been doing research on bio-based polymers for several years, is developing alternatives—including potentially-biodegradable ones—to petroleum-based polymers. These new materials could help reduce plastics-manufacturing-related greenhouse gas emissions. We are investigating the synthesis and functionalization of new bio-based thermoplastics with controlled architectures and bio-based precursors for thermoset resins that allow the macromolecular structures of the materials to be fined-tuned to meet the needs of our partners. We use a twin-screw extruder to transform either polymers we synthesize in the lab or commercially-available bio-based polymers into thermo plastic biocomposites. Produced in pellet form, these materials can be used in plastic injection molding applications. They can also be implemented in key CEA solutions for the energy transition, electronic systems, and the medicine of the future. ■

Bio-based material test samples. The colored samples are natural fibers (linen, hemp, coir); the white sample is a polymer fiber.

Innovations in 3D-printed architected materials

Additive manufacturing, more commonly known as 3D printing, offers a number of advantages. One of these is the ability to create innovative architected materials, which, due to their cellular structures, can outperform the bulk material. The ability to optimize and customize a component's behavior to meet very specific thermal and mechanical requirements depends on solid knowledge of 3D printing processes, materials physics, and implicit and algorithmic design tools. These capabilities also make it possible to respond to specifications very rapidly with a personalized, modular solution. One such innovation developed by CEA-Liten for a partner company is a lightweight, breathable, easy-to-recycle vehicle seat padding material that adapts to the driver's body. ■

Example of a 3D-printed cellular structure.

Metal additive manufacturing improves heat exchanger performance

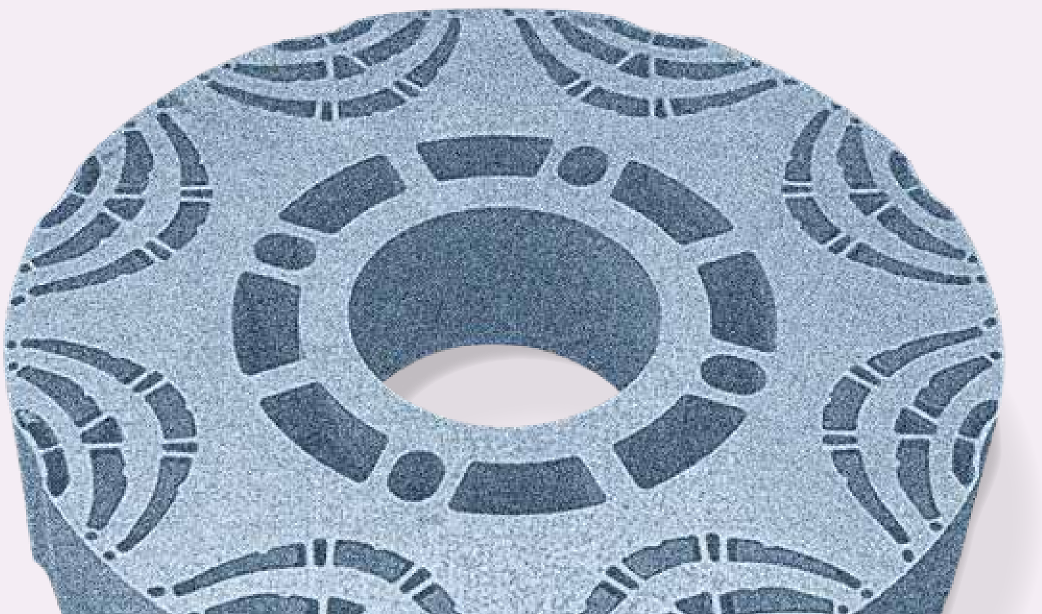
MOTA Group turned to the CEA for support designing a heat exchanger for a marine motor cooling system. The company wanted to utilize additive manufacturing to obtain complex geometries for innovative heat exchangers with optimal thermohydraulic performance. The CEA leveraged its design and modeling capabilities to come up with a concept based on TPMS (triply periodic minimal surface) cellular structures. The particularly compact structure had to be capable of delivering the expected thermal performance. Metal additive manufacturing was used to make a reduced-scale prototype of the complex heat exchanger, both to prove that the concept works and that it can be manufactured. MOTA tested the prototype to verify its thermal performance and identify potential improvements to the dimensioning of this kind of concept. ■

A revolution in magnet recycling for electric motors

One of the main challenges around the magnets used in electric motors is how to reduce their rare earth element content without sacrificing motor performance. Traditionally-shaped magnets can be difficult to access. Often, they are permanently assembled with the motors. This makes removing them for recycling particularly tricky. The disassembly process has to be factored into the magnet design process from the start. CEA-Liten is investigating complex shapes as a potential solution. But conventional subtractive manufacturing methods like machining are not well-suited to the manufacturing of intricate geometries. The removal of material causes significant loss and increased costs.

The Melchior project, a partnership between CEA-Liten and IFPEN, led to the development of an eco-friendly electric motor tailored to automotive industry specifications. The main innovation is the novel shape of the magnets. Not only are the magnets easier to disassemble and remove, but they also improve motor performance. A new process called Power Injection Molding (PIM) was developed to allow near-net-shape manufacturing of permanent magnets.

With power output of 125 kW per kg of permanent magnet and 30% overall material savings, the innovative motor developed outperforms the state of the art. In terms of environmental impact, a preliminary lifecycle assessment showed that the more complex the magnet shape, the greater the material losses during conventional machining, giving PIM a significant advantage. A short-loop recycling process should bring an additional 35% reduction in manufacturing-related greenhouse gas emissions. ■



Specialized R&D facilities for a wide range of technologies

CEA-Liten operates twelve R&D platforms, each with unique capabilities tailored to the technologies being investigated. One thing all the institute's R&D platforms have in common, however, is their focus on testing, modeling, simulation, and characterization—essential to gaining deeper insights into the phenomena at work inside the technologies we develop. The experts who staff our labs have the know-how to put these resources to work to bring our technologies to higher readiness levels.

One example is our research on high-temperature electrolysis (HTE) for hydrogen production. Our scientists and engineers designed and built custom test benches for our early research on HTE components and cells, gradually scaling up our testing capabilities to HTE modules. Having our own test benches is the best way to ensure we have reliable, robust, controlled testing capabilities we can implement in optimal conditions for evaluating a new technology. Our most recent test bench was designed to study the durability of 10 kWDC to 20 kWDC stacks. Built and commissioned in just five months, the test bench will enable 10,000 hours of testing to support the scaleup of the technology. ■

In another project, we had to design our own equipment because what we needed simply didn't exist. Our researchers drew up custom specifications for a high-pressure testing machine to assess hydrogen-gas-induced embrittlement of metal. We also worked with a company called Top Industrie on another H_2 pressure testing machine. The CEA's know-how proved instrumental to the development of this piece of testing equipment. CEA-Liten is currently working with Cetim, France's leading R&D center for the industrial sector, on an in-depth analysis of how materials behave when exposed to hydrogen. The objective is to develop new protocols. ■

Additive manufacturing is another important topic at CEA-Liten. We have developed a unique approach combining experimentation and simulation to optimize metal binder-jet 3D printing. An instrumented test bench representing the printing process was designed and built so that the interactions between the binder and powder bed could be studied and the influencing factors identified. The test bench will generate data that will be used to build and calibrate numerical models of these mainly local interactions. The models will be valuable tools for assessing the impact of binder rheology, powder characteristics, and process parameters on the mesostructure of the material after infiltration of the binder. Ultimately, the new insights gained should help predict and correct printing defects. ■

CEA-Liten's cutting-edge R&D platforms

CEA-Liten's R&D capabilities are organized around twelve platforms, each with advanced equipment, software, and know-how to support the institute's programs. The ability to deploy and test innovations at a near-industrial scale is vital to moving new technologies from the lab to the market. CEA-Liten is constantly investing in new equipment and software to maintain its scale-up capabilities at the international state of the art. Read on to learn more about some of the highlights that marked 2023.

STATE-OF-THE-ART HOT ISOSTATIC PRESSING EQUIPMENT NOW AVAILABLE

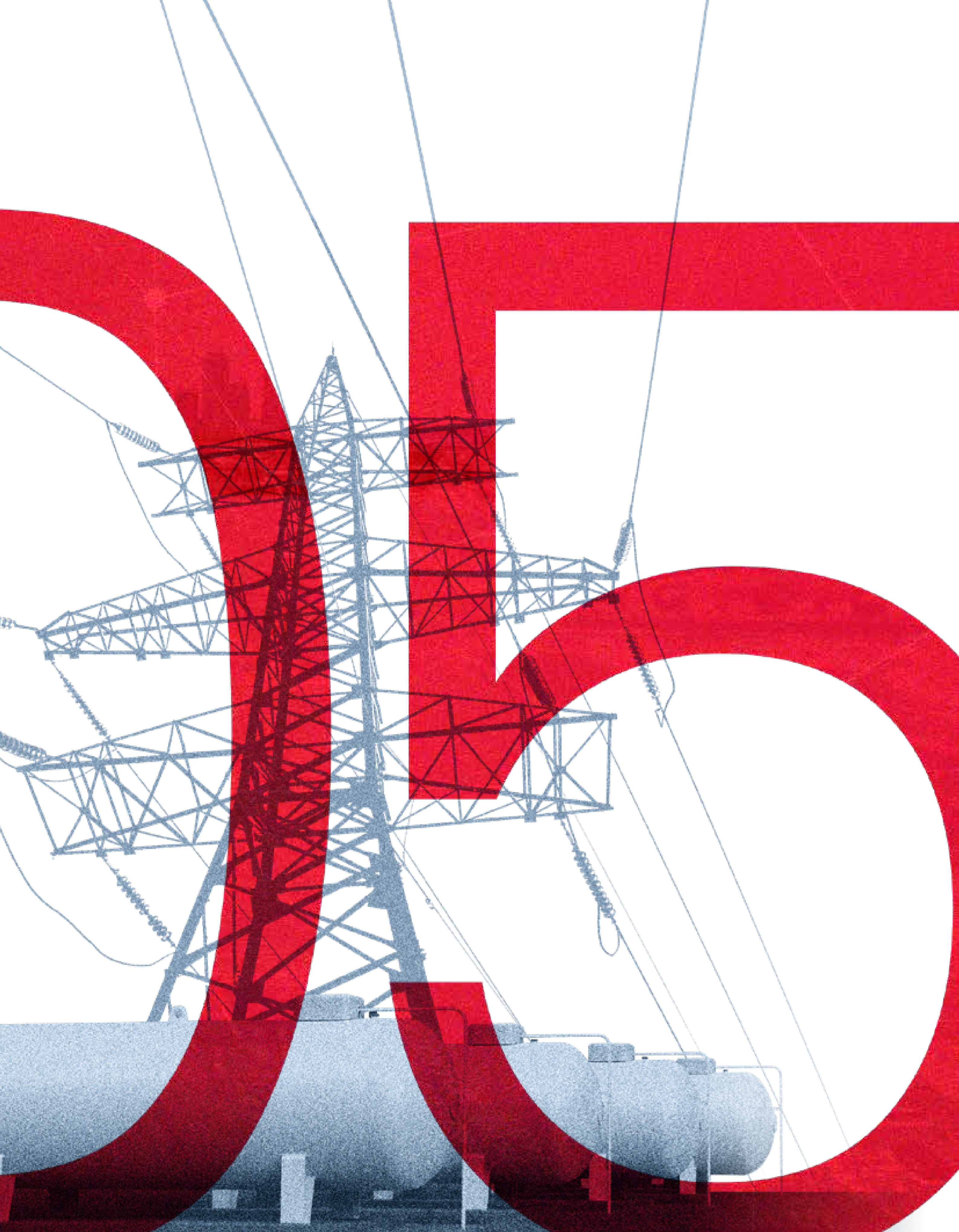
A new hot isostatic pressing (HIP) chamber was installed at CEA-Liten through the national Equipex+ Calhipso project to support the development of a domestic metallurgical industry in France. The 30 L chamber, which started up in 2023, can reach operating temperatures of 1,400 °C and pressures of up to 2,000 bar. It will be used primarily for metals. ■

NEW LAB FOR SMARTER GRID MANAGEMENT

CEA-Liten created its new Grid Control Lab to keep pace with the massive uptick in solar energy production, hydrogen- and battery-based energy storage, and electric mobility. Located on the INES (France's solar energy research institute) campus, this new platform is home to a 20 kV medium-voltage AC loop that can be used on a stand-alone basis or hooked up to the grid for experiments. Real-time micro-grid control systems will also be installed at the platform. ■

ISO 50001 CERTIFICATION FOR CEA GRENOBLE

The CEA campus in Grenoble obtained ISO 50001 certification for its energy management system in August 2023. The certification is evidence of the CEA's commitment to improving its energy performance. CEA-Liten has been working to reduce the energy consumption of its battery drying chambers for a decade, efforts that will continue within the new ISO-certified energy management system. ■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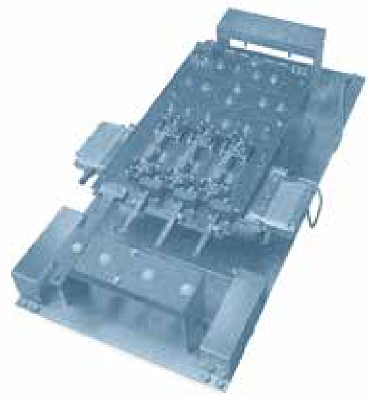
Systems, grids, and energy efficiency



CEA-Liten brings a holistic approach backed by broad know-how to the complex challenge of transitioning to a distributed, intermittent energy system. With expertise at all stages from design to implementation, we are able to optimize energy architectures to meet the needs of our partners. Our solutions always enable energy savings and efficiency and increased sustainability.

We bring a unique vision to multi-technology, multi-carrier, multi-scale energy systems, using simulation, virtualization, *operando* diagnostics, and systems management to develop these solutions to their full potential and help decarbonize the economy. Our research is agnostic, whether that's in terms of energy technology or energy carrier.

Thermal engineering and power converters play a key role in our approach. For example, we are developing software and other solutions to optimize thermal systems, thermal energy storage, and other promising technologies, like Carnot batteries, to decarbonize industrial processes and recover waste process heat.

We are also adapting our power converters to a market that is barely being addressed currently: medium voltage distribution networks.

We are also designing compact, robust, durable converters that require less materials to manufacture. Our preferred materials for these converters are wide bandgap semiconductors like gallium nitride.

“Our solutions always enable energy savings and efficiency and increased sustainability”

Interview with

Alain Ruby

Energy systems modeling
and simulation engineer

01.

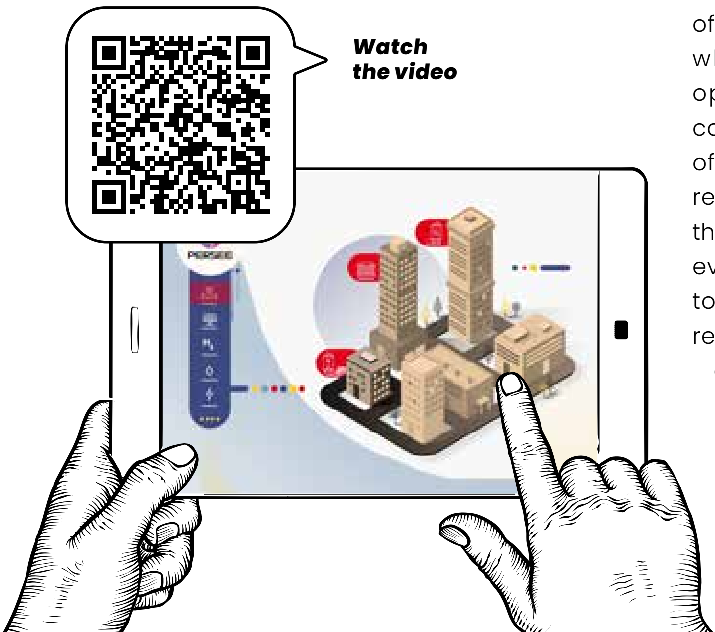
What led to the development of an energy systems optimization tool at CEA-Liten?

The energy transition is no longer up for debate. Public- and private-sector stakeholders are looking for ways to continue to satisfy demand for energy while reducing environmental impacts and lowering costs. Energy systems are complex, and so is choosing the most efficient solutions. Modeling and simulating different scenarios is one way to more effectively dimension the components that make up these systems. We have reached the limits of what today's simulators can do, but operational research has given us access to new methods, which is how PERSEE came to be.

02.

What does PERSEE do?

PERSEE decision-assistance software is used to design, dimension, and operate complex energy systems that can potentially include a variety of energy sources such as electricity, heat, and cold, for example. Energy systems are modeled at scales from individual industrial facility to entire neighborhood. Different technologies can be deployed virtually to assess their impacts on the overall energy mix. One example is comparing a gas boiler with biomass-fueled CHP and decentralized heat pumps to see which solution comes out on top.



Watch the video

PERSEE dimensions and manages the different components of the system optimally over the course of a typical year to meet specific emissions targets while reducing CapEx and OpEx. Shorter-term optimal management trajectories can then be calculated by PERSEE and deployed on a simulator of the real-world energy system to determine how representative the energy mixes recommended by the software are. The goal is to be able to predict and evaluate the real system's performance according to the expected indicators. Because we are able to refine the models and make more realistic energy demand forecasts, we can determine operating conditions that more closely mirror the real-world system. This results in better-informed and more confident decision making. ■

Optimizing complex energy systems

2 Highlights

MICHELIN

The CEA helped automotive tire manufacturer Michelin improve the energy performance of one of its factories. The project began with the development of a comprehensive methodology. A model of the physical plant and its current architecture was created and used to run simulations of multiple scenarios with different technologies. The results of the simulations were then used to determine the optimal architecture for energy efficiency, decarbonization, and water consumption. ■

L'OCCITANE

The L'Occitane en Provence cosmetics plant in the south of France set ambitious self-consumption and water conservation targets with a time horizon of 2030. The CEA used PERSEE to calculate and model an optimal combination of energy technologies including solar photovoltaic, solar thermal, and electrical and thermal storage capacities, plus biomass, heat pumps, and other equipment. The target architecture achieved the best trade-off between the factory's energy efficiency, water savings, and greenhouse gas emissions targets. ■

Aerial view of the L'Occitane en Provence factory in the south of France.

Renovating buildings for greater energy efficiency

Today's existing stock of buildings, responsible for 36% of GHG emissions and 40% of overall energy consumption, is far from sustainable. CEA-Liten is contributing to several projects to move building renovation into the future. The EASI ZERo project, which CEA-Liten is coordinating, will produce a unique catalog of easy-to-install building envelope components capable of improving building thermal performance by 20%. The solutions developed will all be made from bio-based and recycled materials and will be tested on the instrumented buildings on the INES campus.

The CEA is engaged in another project, called AEGIR*, to make building energy renovation projects faster and cheaper. The goal is to develop modular, renewable, and easy-to-manufacture building envelope solutions. ■

CEA experimental buildings used to test envelope components.

** Project financed by Horizon Europe.*

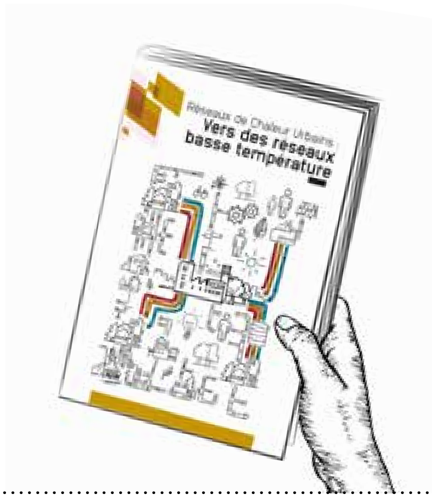
Injecting more green gas into the grid

The energy landscape is changing rapidly, and renewable gas could completely replace fossil-based gas by 2050. Currently around 12 TWh of green gas—enough to supply around three million new gas-heated homes—is injected into the grid in France. The existing grid will need to be managed differently to keep pace with the expected sharp increase in green gas. The CEA and French gas utility GRDF have been working together since January 2023 to increase green gas injection rates to meet demand within the grid's physical limitations. Operational research methods were used to develop an optimization tool specifically for GRDF. The tool determines the best possible operating parameters to maximize the amount of green gas injected while remaining within the grid's operating constraints. The algorithm developed for GRDF was tested successfully on several real-world operating scenarios. These new grid management capabilities will position GRDF to better respond to the challenges of green gas. The utility is using the tool under license from the CEA. ■

Multi-vector energy systems with heat networks

One of the roles of RTE, France's transmission system operator, is to generate multi-vector energy system forecasts. RTE asked the CEA for help modeling heat networks in its Antares-Simulator software for the purpose of studying heat networks' contribution to electricity grid flexibility. A method for modeling different power plants representing different energy mixes in Antares-Simulator was developed. The different heat networks within a given geographical perimeter were also aggregated into a single node representing the entire area so that calculations could be completed on a larger geographical scale. This allowed additional constraints to be applied to the aggregated model and, ultimately, the aggregation of the previously-aggregated models with the various kinds of networks (and their temperatures in the right proportions) into a single model at the national scale. ■

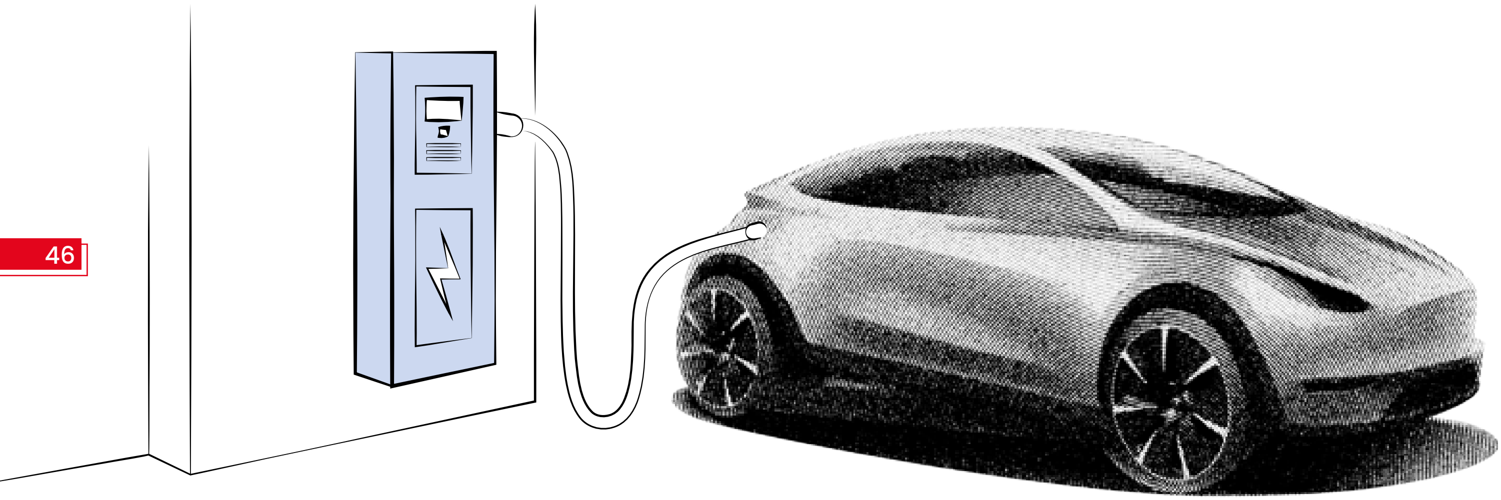
District heat networks are key contributors to a sustainable energy transition. While the majority of these networks are still powered by fossil fuels, we can begin to reduce their GHG emissions now by addressing the issue of operating temperature. Once operating temperatures have been lowered, renewable energy can be brought in to replace today's fossil fuels. This guide, produced under the EU RES-DHC project, has all the information you need to get started. ■



CEA-Liten and startup Storabelle are working together to transform decommissioned power plants into huge energy reserves. The partners will use molten salt thermal energy storage and CEA-Liten's PERSEE optimization software to dimension the equipment.

High-efficiency bidirectional electric vehicle charger

CEA and Renault Group developed a new electronic architecture for a power converter that can be integrated right into the vehicle's charger. The converter, which leverages innovative wide-bandgap semiconductors, will reduce energy losses by 30% during conversion. Heating will be similarly reduced. A ferrite material, used for high-frequency applications, helped make the converter more compact. The converter offers a capacity of 22 kW in three-phase mode for faster charging. But that isn't the only innovation the converter brings: The charger can also be used bidirectionally. Energy stored in the vehicle's battery can be fed back into the grid when intermittent renewable energy is unavailable or to supply homes in self-consumption scenarios, for example. ■



Together for better battery management

Vitesco Technologies and the CEA developed SWIBA, an innovative automotive energy management technology that addresses each cell in a battery pack individually. The cells are connected to power switches that can either connect the cells to each other or remove a cell for dynamic real-time testing. SWIBA selects the cells optimally based on their characteristics and on the vehicle's operating mode. Managing battery cells individually reduces phenomena that affect aging, increasing the battery pack's lifespan and optimizing the management of available energy. Overall system performance also benefits, for increased vehicle range and faster charging. Measurements on a demonstrator system showed a 6% longer vehicle range, 20% shorter charging time, and 15% longer battery life. Finally, the system also makes second-life usage of spent automotive batteries easier. ■

A closer look

New converter architectures for high-power photovoltaic plants

BACKGROUND

Gradually extending PV technology into the medium-voltage range [1] would be one way to overcome some of the disadvantages of today's solar power plants. CEA-Liten researchers designed a new power converter with an integrated galvanic isolation for future generations of solar power plants. This new converter will allow longer and, therefore, more powerful, PV strings to be used. It will also enable a direct connection to the grid without the need for bulky 50 Hz transformers. This advance won the Young Researcher Award at PCIM 2023.

METHODOLOGY & RESULTS

SiC power modules are now available in medium voltage ratings, which makes efficient, high-power-density medium-frequency power electronics transformers possible. The proposed MV architecture (Figure 1) leverages a resonant topology for the isolated DC/DC converter whose series connection is connected to a DC/AC converter (MMC)[2].

The power electronics building block (PEBB) consists of two cascaded conversion stages. First, a three-stage chopper is implemented for maximum power point tracking (MPPT) followed with a power electronics transformer made up of two single-phase resonant inverters [3]. This provides a galvanic isolation between the 2 kV PV field and the intermediate MV DC collector (42kV). The electronic transformer test bench is built of an input power stack (1.7kV SiC MPPT boost, Voltage Source Inverter, DC caps, and heatsink) and an output power stack (3.3kV SiC rectifier and heatsink), two transformers operating each at 20 kHz (2 x 30kg manufactured by CEFEM), and resonant capacitors. Characterization of the unit power converter was carried out on equipment at CEA-Liten's new Grid Control Lab.

Figure 2 shows the electronic transformer's total losses and overall efficiency. A peak efficiency of 99.06% was obtained at 140 kW input power and is nearly maintained, over 60% of the operating range [4].

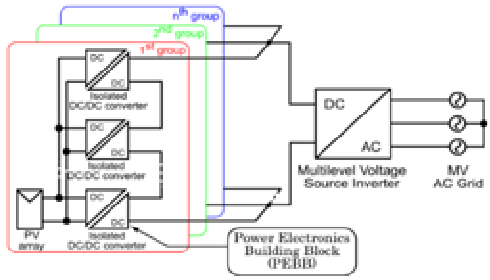


Figure 1: *Modular converter system with MVDC collector.*

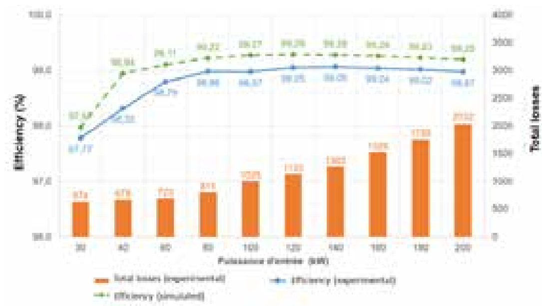


Figure 2: *Waveforms at maximum power and conversion efficiency (Vin=2 kV, Iout=100 A).*

CONCLUSION

The next step will be to build a MVDC demonstrator >2kV to be connected to the MVAC MMC converter [5]. Several prototype blocks will be combined and MF transformers that meet the dielectric requirements of the MVDC collector will be developed and optimized. Interactions between MV collectors and MMC converters and/or electrified rail and/or transportation networks will also be investigated.

LEARN MORE

[1] *A. Bier, O. Wiss, and P. Messaoudi, "A 3 kV, 20 kW Medium-Voltage PV Plant Demonstrator," p. 8, 2017.*

[2] *M. N. Ngo, P. Ladoux, J. Martin, and S. Sanchez, "Silicium-Carbide-Based Isolated DC/DC Converter for Medium-Voltage Photovoltaic Power Plants," Energies, vol. 15, no. 3, p. 1038, Jan. 2022, doi: 10.3390/en15031038.*

[3] *M. N. Ngo and P. Ladoux, "Performance Evaluation of SiC MOSFETs for Isolated DC-DC Conversion in Medium Voltage Photovoltaic Power Plants," p. 9, 2022.*

[4] *M. N. Ngo, P. Ladoux, and S. Dumenil, "Implementation and Characterization of a 200-kW Full-SiC Isolated DC/DC Converter for Future Medium Voltage PV Plants".*

[5] *M. N. Ngo, J. Martin, P. Ladoux, and S. Sanchez, "Comparison of High-Power DC/AC Converters for Medium-Voltage PV Power Plants". 10.1109/EEE-AM58328.2023.10395366.*

Events

CEA-Liten had a busy event calendar again this year, both in France and abroad. In addition to exhibiting or presenting at trade shows like Hyvolution, MIX.E, and CES, we also organized the Nanosafe conference in Grenoble. Nanosafe is the place to be for experts in nanomaterials, one of CEA-Liten's specialties. Trade shows are a great way to showcase our leadership in innovation in our areas of expertise!

1. *Hyvolution*
2. *EUPVSEC*
3. *Nanosafe*
4. *MIX.E*
5. *CES*

RD20 summer school puts decarbonization and R&D at the center of a sustainable future

The RD20 summer school was launched at the G20 summit in Japan. A cohort of around 60 PhD students, post-docs, and other early-career scientists from fifteen countries attended the inaugural session at Prapoutel, a ski resort near Grenoble, France, in July 2023. The session offered a unique opportunity to share knowledge about the decarbonization of energy systems and the associated R&D challenges.

The summer school is a forum for exchange designed to encourage the emergence of recommendations for RD20 stakeholders to support the attainment of Net Zero targets. During the week-long seminar organized by the CEA and CNRS, the early-career scientists in attendance brought their unique perspective to the challenge of making our societies carbon neutral and formulated a set of global recommendations.

Their work was guided by high-level speakers, all experts in their fields, who taught classes on solar, wind, smart grids, hydrogen energy, energy storage, bioenergy, carbon capture and usage, plus learnings from the social sciences and humanities. Their final recommendations address waste recycling, energy savings and efficiency, critical materials, the need for shared indicators, the integration of energy transition issues into educational programs, and how to better incentivize the carbon market and make it more equitable.

The idea is for research organizations in G20 countries to challenge their national governments on energy issues. The recommendations that came out of this first RD20 summer school will be presented at the next G20 summit to influence policy and help drive the transition to a more sustainable future. ■

Working at CEA-Liten

Read why some of our recent hires chose CEA-Liten:

Sebastien KAWKA

"I chose CEA-Liten for scientific excellence in the field of fuel cells and batteries, more precisely concerning numerical simulations. CEA-Liten has not only the tools, but also the ability to apply them to real-world systems."

Polyxeni TSOULKA

"CEA-Liten's activities sit somewhere between academic research and industrial R&D. At my lab, for instance, we are working on the latest generation of solar cells. We are looking for processes that can be scaled up so that we can bring these new materials to the market. I find that particularly motivating."

Elie GHANATOS

"When you work at CEA-Liten, you play an active role in the energy transition. As a research and technology organization, our work is anchored in the real world. To transfer our innovations to manufacturers, they have to be applicable to real-world use cases and manufacturable."

Johannes AST

"At CEA-Liten we have access to a wide variety of instruments to study very complex materials like perovskites and materials for fuel cells. Generating new insights into how these materials behave helps us better understand the associated use cases."

You too!

Do you want to get involved in the energy transition?
Check out our job openings and apply at **www.emploi.cea.fr**

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We would like to thank all our partners and financers.

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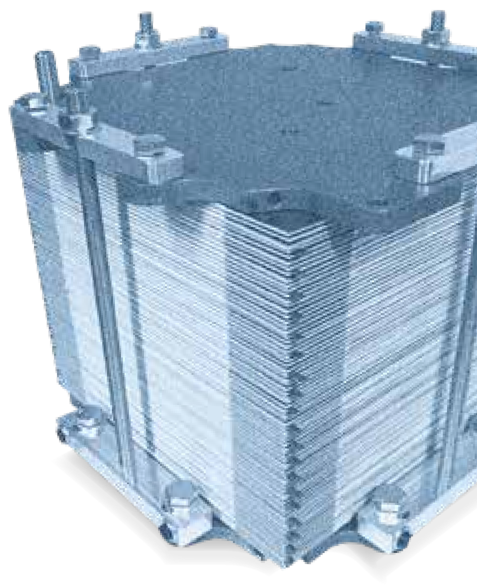

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