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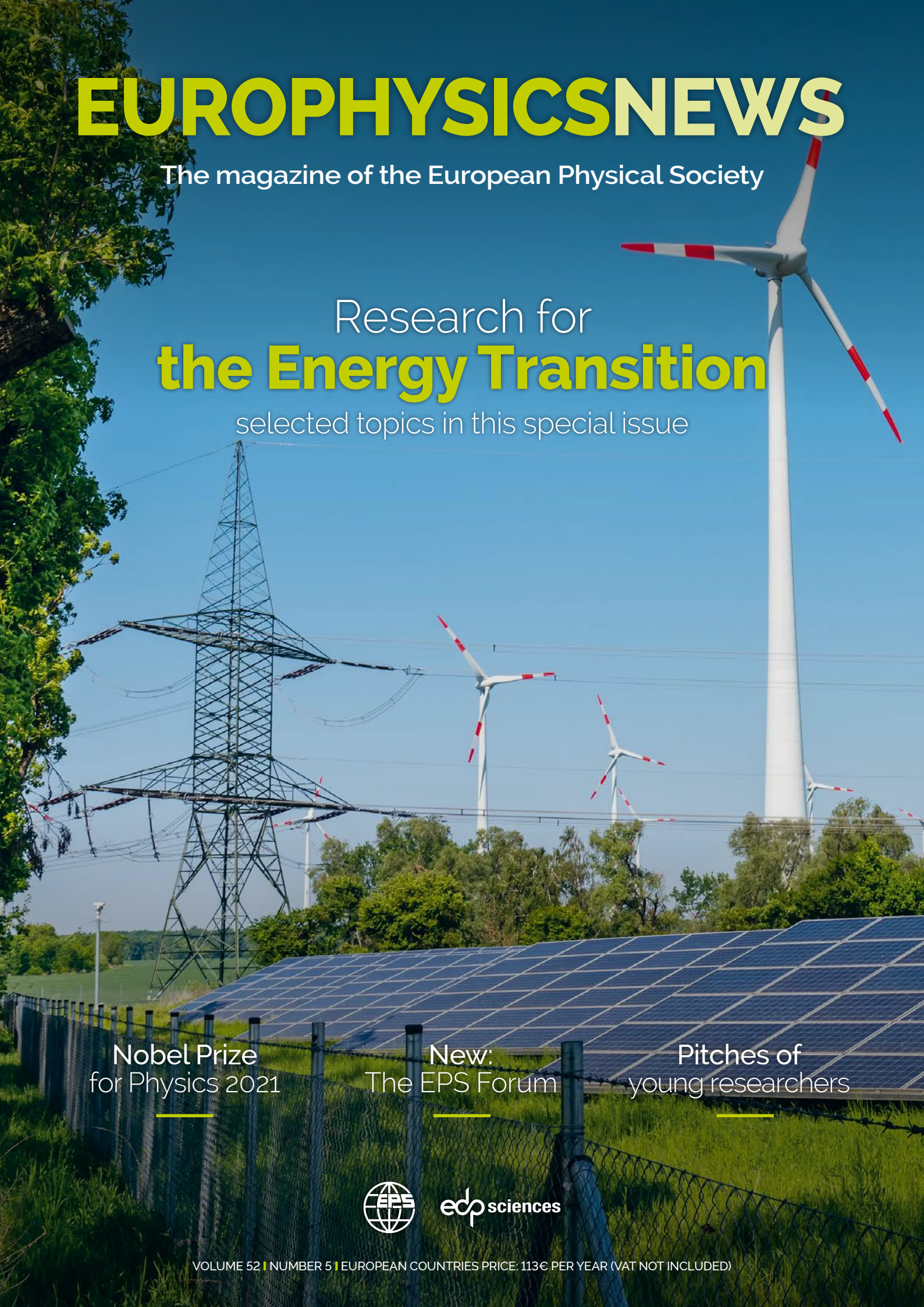

Research for the Energy Transition

selected topics in this special issue

Nobel Prize for Physics 2021

New: The EPS Forum

Pitches of young researchers

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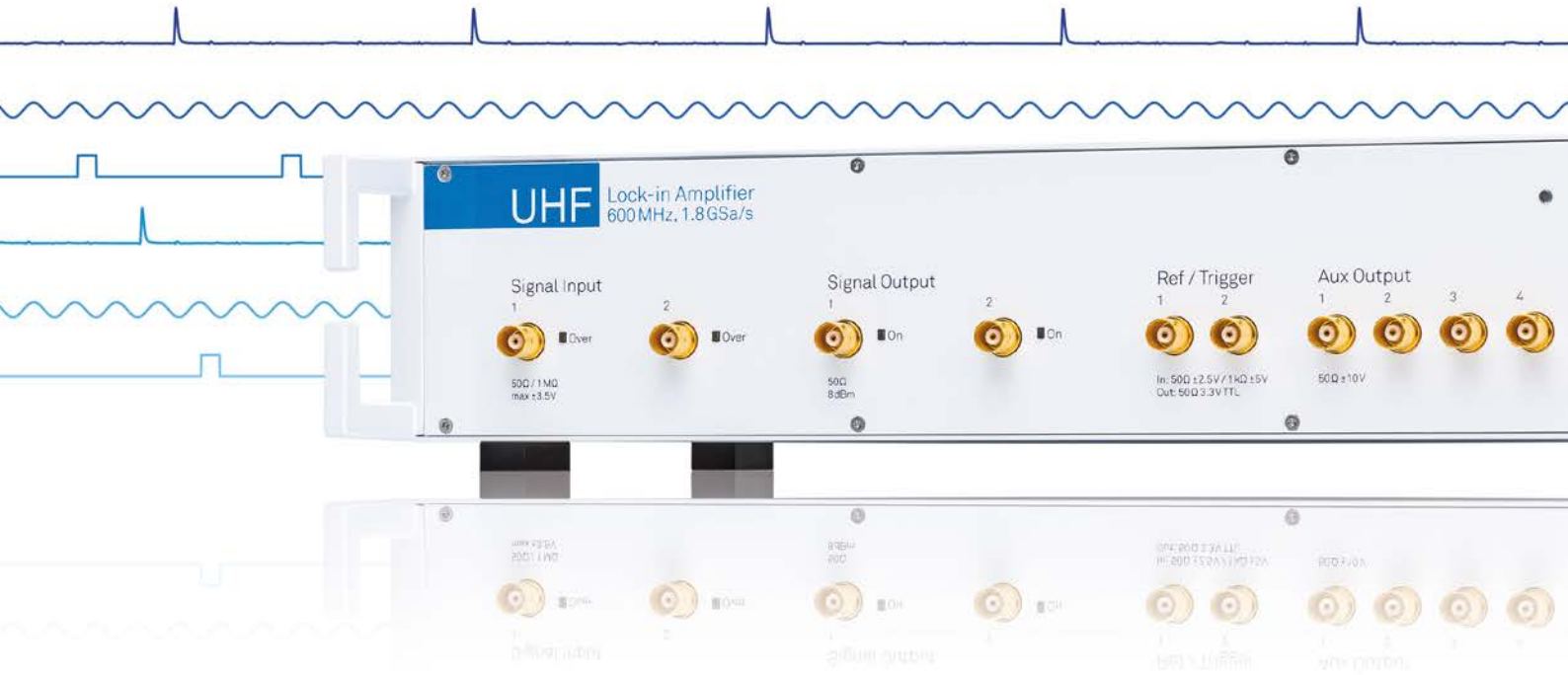

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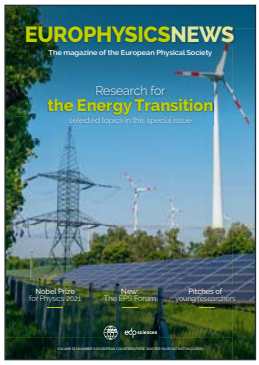

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Cover picture: Solar panels, wind turbines and the electricity grid: three items addressed in this issue. © iStockPhoto.

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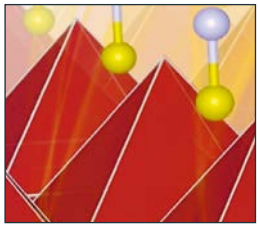
First edition of The EPS Forum



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[EPS EDITORIAL]

Let us meet at the EPS Forum!

The European Physical Society (EPS) is known for its commitment to support academic research in physics in Europe and all over the world, to help young researchers and promote science by all means. One of these means consists of organising conferences that attract hundreds or even thousands of physicists. Europhysics conferences are nowadays viewed as essential on our continent, overseas, and in Asia. They provide an essential place for the exchange of ideas between researchers and the pleasure of meeting up with colleagues. Even if the covid crisis has considerably slowed down the opportunities to exchange face-to-face, in-person meetings are gradually coming back, as evidenced by the *"Rencontres Physique Entreprise Recherche"* (RPER) that gathered several hundreds of participants in Paris on the 17th of September 2021. Despite the tremendous development of online meetings and webinars, something is missing when we are not physically together, in the same place and at the same time.

If the organisation of international conferences is a key activity of the EPS, it is clear that only few events have so far allowed its members to meet regularly and directly address the latest achievements in science, the career of our young researchers, the diversity of our community and the concerns of our learned societies. In the past the General Conference of the EPS, combining high-level plenary talks and panel discussions on societal aspects, survived for several decades before vanishing after 2005. Yet, the EPS remains an essential learned society which accompanies the various paths of our community members. Representing more than 100,000 physicists across Europe, it is an umbrella organisation for 42 national physical societies and federates 18 scientific divisions and groups. Despite this wealth, the only opportunities to meet together remain the EPS Council, where the representatives of our numerous bodies listen to business reports and proceed to votes, and the General Assembly, in principle held every three years and which often goes unnoticed.

This is the reason why I proposed to set up a major meeting between young researchers and industrial partners, between scientific experts of the highest level, representatives of the EPS Member Societies and board members of the EPS divisions and groups. This meeting has a name: the EPS Forum. It will precede the EPS Council and should become the main showcase of our Society in the future. It will differ from previous EPS congresses by including actors of the industrial sector who will actively take part as both organisers and participants, and by promoting both the highest achievements in physics and the youngest of our members.

The first edition of the EPS Forum will be held the 2nd through the 4th of June 2022 at the International Conference Center of Sorbonne University in Paris. On this occasion 10 member societies, half of the EPS divisions and groups and 10 associate members accepted to form the programme and organisation committees, gathering more than 70 active members. Structured around various scientific themes such as energy, accelerators, quantum technologies, machine learning, condensed matter and artificial intelligence, the EPS Forum will take place over three days:

- Day 1 will be dedicated to the employment of young physicists in Europe and favor direct exchanges with CEOs, directors and engineers of major industrial companies in these fields.
- Day 2 will address the scientific and societal challenges facing the physics community. The latest achievements in physics will be highlighted by the most outstanding experts. Societal issues will also be debated in the presence of prominent representatives of the European Commission.
- Day 3 will host the EPS Council.

Already more than 20 companies and several Physics Nobel laureates agreed to jump on board and attend the EPS Forum in Paris. So, be prepared for this new, great event by having a look at www.epsforum.org and let us all meet at the EPS Forum! ■

■ **Luc Bergé,** *EPS President*

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Unique online Joint EPS-SIF International School on Energy

The sixth edition of the Joint EPS-SIF International School on Energy under the 'energetic' leadership of the directors of the school, Prof. Luisa Cifarelli and Prof. Francesco Romanelli, took place online from 19 to 23 July 2021. This year, the focus of the school was "Energy Innovation and Integration for a Clean Environment". There were 55 students and 20 teachers from all over the world, including India and Russia, that participated in the school. A very complete range of energy-related topics were presented: renewable energy systems, energy storage, fission and fusion, including a talk on the impact of the Covid-19 pandemic on energy perspectives.

Due to the pandemic we had to miss the beautiful and stimulating environment of Villa Monastero, in its superb location in Varenna, Lago di Como. Despite initial fears for breakdowns of the connection, technical problems were reduced to an absolute minimum thanks to the help of the professional IT team. Although the attendance was remote, there was nevertheless a pleasant interaction between lecturers and students, further enhanced by the online "Get together hallway" at noon and during the virtual afternoon coffee break with often very lively discussions.

The concepts and ideas involved in modern energy systems were clearly exposed by the lecturers that invested every effort to be as didactic as possible. On Tuesday, Wednesday and Thursday, the students had the opportunity to present their own topic of research during the "Student Talks" and the three best presentations were awarded at the closure of the school. A unique aspect of the school is its multidisciplinarity, a characteristic that is rarely found in schools and meetings on energy. It is very important to get a good overview of the complexity of the energy problem, for which there is no unique and no easy solution, because energy systems are not only strongly interlinked themselves but also intimately connected with economy, society and environment, *i.e.*, the general well-being of all citizens on earth.

The lectures will be published by the SIF as Lecture Notes, in a dedicated hardcover edition, nicely complementing the five earlier editions. They will be also available on-line on the EPJ Web of Conferences. It seems rather certain that this publication, which summarises the unforgettable and interesting week, will serve as a reference for years to come. I highly recommend this school to all scientists interested in the energy debate. ■

Jef Ongena, *Chairman of the EPS Energy Group and Research Director of the Plasmaphysics Lab, Royal Military Academy, Brussels, Belgium*

▲ A "zoom" picture of all participants in the 6th Summer school.

Prof. Eliezer Rabinovici
is the new President of the CERN Council

On the 24th of September 2021, The CERN Council announced the election of Professor Eliezer Rabinovici as its 24th president, for a period of one year, renewable twice, with a mandate starting on 1 January 2022.

Eliezer Rabinovici is Leon H. and Ada G. Miller professor at the Racah Institute of Physics, The Hebrew University of Jerusalem, and holds the Louis Michel Chair at the *Institut des Hautes Études Scientifiques* (IHES) near Paris, since September 2015.

The area of research of Eliezer Rabinovici is theoretical high-energy physics, in particular quantum field theory and string theory. He received his PhD in high-energy physics at the Weizmann Institute of Science in 1974. In the following years, he worked as a research associate at Fermilab and at Lawrence Berkeley Radiation Laboratory, before returning to Israel and the Hebrew University as a senior lecturer in 1977, where he served as Director of the Racah Institute as well as the Director of the Institute of Advanced Studies from 2005 to 2012.

Professor Rabinovici has made major contributions to the understanding of the phase structure of gauge theories, which are the building blocks of the Standard Model, and the uncovering of the phases of gravity. Throughout his career, he has held positions within several councils and committees, such as member of the HEP Board of the European Physical Society (EPS - from 1996 to 2011), Chair of the Israeli Committee for SESAME (since 1997) and Chair of the Israeli High-Energy Committee (from 2004 to 2020). In 2004, he was appointed as one of Israel's delegates to the CERN (European Organisation for Nuclear Research) Council, where he served as Vice President from 2016 to 2018. Since 2018 he has also been a member of the EPS Executive Committee.

▲ Professor Eliezer Rabinovici

"CERN is a special place where science and collaboration meet to answer some of the most fundamental questions about the world we live in. Throughout my 16 years as a member of the CERN Council, I have time after time been captivated by the commitment, collaboration and knowledge of people who work together towards the same mission. I am honoured that the Council chose me as their next President, and thankful that I get the opportunity to serve CERN's scientific community, Member States and Associate Member States," said Professor Rabinovici.

According to the Convention for Establishment of the European Organisation for Nuclear Research, promulgated by the twelve founding members of CERN, the Council is the supreme decision-making authority of the Organisation, composed by delegates of all its twenty-three Member States.

The Council determines CERN's policy in scientific, technical and administrative matters, defines its strategic programmes, sets and follows up its annual goals, and approves its budget. The Council also appoints the Director-General who is the Organisation's chief executive officer and legal representative. The Council typically meets four times a year, chaired by the President, with the Director-General acting as Secretary.

The European Physical Society warmly congratulates Professor Eliezer Rabinovici for his election at this very prestigious position and wishes him a full success in the future endeavours of CERN under his guidance. ■

They work on the energy transition

EPN invited young researchers who participated in the Joint SIF-EPS Energy School 2021, to present themselves and their research project. Meet the young generation working in research for the energy transition.

Giulia Spaggiari

I work on materials for solar cells. I am about to finish my first year as a PhD student in Physics at Parma University, in collaboration with the Institute of Materials for Electronics and Magnetism (IMEM-CNR). I am working mainly on new materials for photovoltaic applications, with a special focus on multilayer structure and the possibility of applying Raman spectroscopy with an innovative approach to study them. Antimony Selenide is the material I'm focusing on right now, because it is a very promising alternative material for solar cells. Antimony Selenide (Sb_2Se_3), indeed, is attracting more and more interest thanks to the great promise coming from its theoretical PCE limit (calculated by the Shockeley-Queisser model) around 32.2%. Moreover, it is a low cost and not toxic material, which is based on abundant and easily available elements. Climate change and global warming are the biggest challenges the human kind is about to face and trying to help solving these huge issues, even adding a small gear to the green-transition machine project, is really important and motivating to me. ■

Antonin Berthe

I work on modelling the effects of the energy transition. I am a PhD student at STEEP and ISTerre studying the feasibility of energy transition integrating interacting constraints. The STEEP team is interested in modelling global systemic risks induced by planetary limits and the complexity of our societies, Olivier Vidal's team is designing a model of raw material and energy flows following the sectors of our societies. In this context, my work aims at questioning the feasibility of an energy transition through the design of a dynamic system model. My thesis, beginning this year, aims at adding physical and industrial constraints to a dynamic model of the trend evolution of energy and material flows in different regions of the world. Through this ongoing modelling , I will study the strong constraints in raw material supply, in land use and in annual growth of technologies, as well as the constraints on electrical grid. This work is particularly motivating because it seems really useful to me, at a time when the energy transition is proposed as an implicitly possible solution to climate change, even though we do not know all the impacts that it could have, nor if it is really physically possible. What are the main constraints for energy transition? Is it even possible? ■

Chiara Mancinelli

I work on improving the technology for heat pumps. I am currently in my last year as a Ph.D. student in Industrial Engineering at University of Rome "Tor Vergata". My research fields revolve around energy efficiency, decarbonisation, Thermal Energy Storages (TES) with Phase Change Materials (PCMs) with a focus on electrification of heating and cooling by means of energy conversion systems based on natural refrigerants, such as transcritical CO_2 heat pumps. Energy transition urges the importance of taking actions upon not only renewable energy sources but also sustainability and efficient systems, by reducing consumption and CO_2 emissions in the heating and cooling sectors. Electrification is widely recognised as one of the most promising solutions, therefore heat pumps are receiving increasing consideration. The purpose of my research is to develop a transcritical CO_2 heat pump characterised by an efficient and simple way of increasing the overall performance: in the proposed system, thermal energy is temporarily stored in a stratified water tank and used later to increase the evaporation temperature and reduce the compressor's work. Basically, it is an internal energy recovery that enhances global Coefficient of Performance (COP) thanks to these discharging cycles, with the advantage of not having any additional equipment and installation costs. Moreover, when there is no heating or cooling demand, energy can be stored and then released later in time thanks to PCMs (Phase Change Materials) at different temperatures. The study is carried out in the context of a research project whose industrial partner is the Italian company Dorin, leader in CO_2 compressor manufacturing. ■

Ankush Kumar

I work on better Lithium-ion batteries. I am a PhD student working on "Recycling of Spent Lithium-ion Batteries (LIBs)" with Dr Venkatasailanathan Ramadesigan and Dr S. Srinivas in the Department of Energy Science and Engineering at the Indian Institute of Technology Bombay (IITB), India. I completed my Master's degree in Energy Science at IITB, where my dissertation was on "Assessment of Energy Requirement in the Recycling of Spent LIBs". LIBs are used presently in the green energy transition in various sectors like transportation, portable electronics, and grid-scale stationary energy storage systems due to their portability and high energy and power density. Such extensive use of LIBs will generate tons of spent LIBs as e-waste in the coming years. Therefore, recycling of spent LIBs is necessary and offers many benefits like (i) avoiding environmental damage from the dumping of spent LIBs, (ii) lowering the indirect GHG emissions from the mining and production of rare (cobalt, nickel, lithium) and abundant (copper, aluminium) elements and (iii) reducing the overall energy and emission footprints of LIBs. Further, recycling spent LIBs can improve the raw material supply chain security.

Currently, I am developing an environment-friendly recycling process through combined hydro- and pyro-metallurgical techniques for spent LIBs. ■

Garima Aggarwal

I work on the development of more efficient solar cells. I am a postdoctoral fellow at IIT Bombay, India. I work in the field of solar cells; materials to device fabrication. There is a global drive to move towards renewable energy as conventional fossil fuels are limited and have a negative environmental impact. In this aspect, solar photovoltaic is able to reach individual households, public places, and industries to meet the electricity demand. Towards this, researchers are exploring various materials and innovative device architectures to make it affordable as well durable. In my Ph.D., I worked on one such material: Cu_2O that is non-toxic, earth-abundant, and can be processed at a low cost. I investigated the fundamental properties to understand the reason for its inferior performance in solar cells and proposed solutions to improve it. I prepared samples from three different synthetic routes to include the effect of microstructural properties as well as intrinsic defects. Along the way, we demonstrated a novel method to produce single crystals of Cu_2O by annealing the Cu-foil for 5 h in contrast to conventional 2-3 days. My study concluded that, unlike Si, making monocrystalline cells of Cu_2O is not the solution, however, external doping to neutralise its intrinsic defects will improve the efficiency of Cu_2O based solar cells. ■

Akhilender Jeet Singh

I work on a photocathode for hydrogen production. I am a Ph.D. student at the Dept. of Energy Science & Engineering, IIT Bombay, India. My research is focused on Nanostructured Cu_2O Photocathode for Hydrogen Production. To satiate the global demand for next-generation fuel, hydrogen, innovative and sustainable techniques are required. Photoelectrochemical (PEC) water splitting is one such technique to produce hydrogen leaving behind no carbon footprint. A PEC cell comprising semiconducting electrodes absorbs sunlight and splits H_2O molecules into H_2 and O_2. The objective of my research is to fabricate low-cost and highly efficient semiconducting light absorbers for a PEC cell. Currently, I'm working on nanostructuring of Cu_2O - an earth-abundant and non-toxic material - to improve its performance in PEC cells. The Cu_2O thin film is electrodeposited on a transparent conductor (FTO) and is subjected to an electrochemical treatment. The surface morphology is transformed from micrometre-sized dense pyramids to 10-30 nm thick flakes after voltage cycling in a pH 5 media. The effect of morphology change is evinced as the photocurrent improves by more than 50 %. This enhancement is due to the advantages of nanostructured Cu_2O thin film such as orthogonal charge separation, better light trapping, and increased electrode-electrolyte contact area. I believe that a PEC water splitting device is a strong contender among renewable energy sources. ■

The Nobel Prize in Physics 2021

Ulrich Platt, Johannes Orphal, Christian von Savigny
Board of the Environmental Physics Division of the European Physical Society

The Nobel Prize in Physics 2021 was awarded "for groundbreaking contributions to our understanding of complex systems" with one half jointly to Syukuro Manabe and Klaus Hasselmann "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming" and the other half to Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

Klaus Hasselmann

Prof. Dr. Klaus Hasselmann is a pioneer of climate modelling. In the 1970s, he published the first stochastic climate model (*e.g.* Hasselmann 1976) solving the problem of separating short term variations in the Earth system (*i.e.* largely weather phenomena treated as "noise") from long term responses of *e.g.* the ocean and the biosphere. In these models the evolution of the climate probability distribution is described by a Fokker-Planck equation, in which the effect of the random weather excitation is represented by diffusion terms. This approach was important for the discussion where voices like "we can't even predict next week's weather, how should we be able to predict the climate of the next decades?" were prominent. He was also one of the first to demonstrate (*e.g.* Hasselmann 1993) the signature of human activity in the climate records of the previous 20 years with a confidence of 95 percent (today the confidence is even higher). Until his retirement in 1999, Hasselmann was director of the Max-Planck-Institute of Meteorology in Hamburg and scientific director of the German Climate Computing Centre (DKRZ), in the founding of which he was a central actor. He has received many prestigious awards such as the James MacElwane Medal of the American Geophysical Union, the Physics Price of the Göttingen Academy of Sciences, the Sverdrup Gold Medal of the American Meteorological Society, the Körber Award for European Science, the Symons Memorial Medal of the Royal Meteorological Society, and the Vilhelm-Bjerknes-Medal of the European Geophysical Union. ■

Giorgio Parisi

Prof. Parisi studied a broad range of topics (see Parisi 1992) making important contributions to the theoretical physics of elementary particles, quantum field theory, and statistical physics, in particular of systems with frozen disorder, *i.e.* systems which are not in thermodynamic equilibrium. A typical example of such systems are spin glasses (disordered systems exhibiting ferromagnetic, and anti-ferromagnetic spin-spin interactions) where collective processes rather than energy barriers can lead to extremely long relaxation times. He also made important contributions to climate research, *e.g.* with his research on stochastic resonance in the climate system. Dr. Parisi is professor of Quantum Theories at the Sapienza University of Rome. He has received very prestigious awards, such as the Wolf Prize, the Lars Onsager Prize (American Physical Society), the Max Planck Medal (Deutsche Physikalische Gesellschaft), the Enrico Fermi Prize (Società Italiana di Fisica), the Dirac Medal (International Centre for Theoretical Physics), the Boltzmann Medal (IUPAP), and many others. ■

Syukuro Manabe

Prof. Manabe truly is one of the pioneers of numerical climate modelling; he created the first atmospheric models in the 1960s at the NOAA (National Oceanographic and Atmospheric Administration) Geophysical Fluid Dynamics Laboratory (GFDL). These models were relatively simple, but already considered important effects, such as the water-vapour feedback or atmospheric convection. Together with colleagues, Prof. Manabe carried out the first realistic simulations of the global surface temperature response to a doubling of atmospheric CO_2 (Manabe and Weatherald, 1967). He is also famous for performing the first climate simulations with a coupled atmosphere-ocean model in the late 1960s (Manabe and Bryan, 1969). Prof. Manabe's work on climate modelling and climate sensitivity formed an essential basis for the first assessment report of the Intergovernmental Panel on Climate Change (IPCC). Prior to receiving the Nobel Prize in physics, Prof. Manabe has received a number of high-ranked research awards including the AMS (American Meteorological Society) Carl-Gustav Rossby Research Medal and the EGS (European Geophysical Society) Milutin Milankovic Medal. ■

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The discovery of a new organization of matter

Felix Ritort – Small Biosystems Lab, University of Barcelona

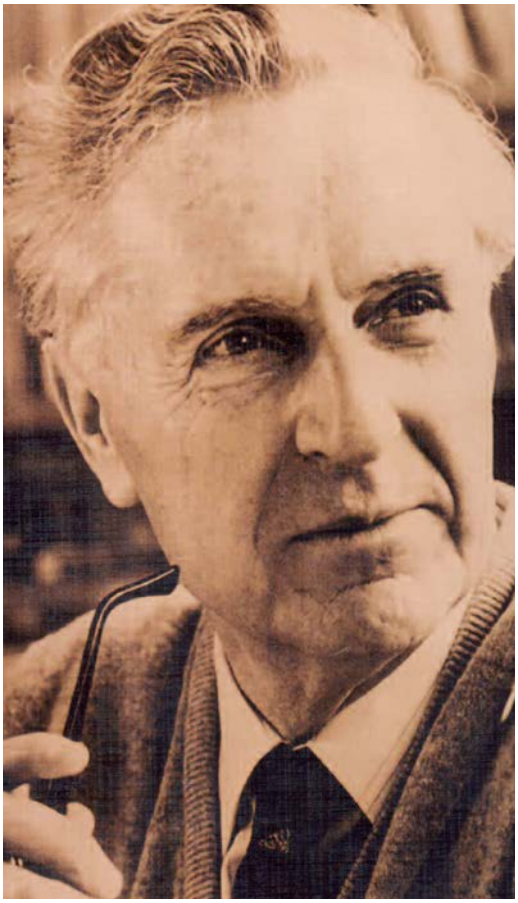
This year Giorgio Parisi was awarded the Nobel Prize for Physics for his discoveries in disordered and complex systems. Parisi's award has been long-awaited and celebrated by the statistical physics and complex systems community.

Parisi carried out his physics studies at the University of Rome, "La Sapienza," culminating his Ph.D. in 1970 under the supervision of Nicola Cabibbo in the field of quantum chromodynamics. In the '70s, Parisi made key contributions in particle physics, such as the parton model for hadron collisions with Guido Altarelli. Parisi could have just built a scientific career in particle physics like many of his colleagues did. However, Parisi's curiosity is immense, being attracted by statistical mechanics and its beauty. In the '70s, Parisi enjoyed frequent stays in Paris, making key contributions in the theory of planar diagrams and matrix models (with Brezin, Itzykson, Zuber) and supersymmetry and dimensional reduction (with Sourlas). These activities spurred what soon became his most fruitful and creative scientific period. During the '70s, spin glasses were a key topic in condensed matter physics. Spin glasses are metallic alloys where magnetic impurities (Fe,Mn,...) polarize conduction electrons generating ferromagnetic and antiferromagnetic interactions between the impurities. These conflicting interactions lead to the emergence of magnetic frustration and a spin-glass temperature Tg below which spins freeze in random directions. There is no long-range magnetic order in the spin-glass phase, and slow relaxational processes and irreversible phenomena are common. In 1975 Edwards and Anderson (Nobel Laureate 1977) developed an elegant mean-field theory with spins interacting through random couplings. The model's solution was based on the replica trick, a mathematical method where the system's Hamiltonian is replicated n-integer times followed by the analytical continuation. The model showed a phase transition, the order parameter being the spin-spin overlap between two different replicas. In the same year, Sherrington and Kirkpatrick solved the infinite-ranged version of the Edwards-Anderson model, finding an infinite number of solutions. The simplest choice (replica symmetry) gave negative entropies at low temperatures. In a magnetic field, a similar instability of the replica symmetric solution was found by De Almeida and Thouless (Nobel Laureate 2016). It was then clear that replica symmetry had to be broken. But how? Bray and Moore from Manchester tried a breaking scheme (the two-group model) that failed (it was shown later that this scheme describes metastable states in disordered models). In 1979, Parisi discovered the correct replica-symmetry breaking (RSB) scheme. The solution was an iterative, exactly solvable scheme of boxes within boxes for the overlap replica matrix (such as in nested Russian dolls) that restored thermodynamic stability and positive entropy. De Dominicis and Kondor demonstrated the stability of Parisi's solution close to Tg, yet the rigorous demonstration of its correctness had to wait until 30 years later. Parisi interpreted RSB as a new organization of matter with a multiplicity of amorphous phases. In the decade of the '80s, in collaboration with M. Mezard and the late M. Virasoro, Parisi set the basis of spin-glass (SG) theory. Disordered systems contain many distinct pure states with exponentially distributed free energies unrelated by symmetry but hierarchically organized in an ultrametric tree. Many applications of SG theory soon emerged, from neural network models by Hopfield, Gardner, Amit, Sompolinsky to optimization theory in computer science (matching, partitioning, traveling salesman problems), general satisfiability problems (*e.g.*, random K-SAT and the survey propagation algorithm). The 80's also witnessed important contributions such as a multifractal description of fully developed turbulence, the Kardar-Parisi-Zhang equation for random interfaces, and the stochastic resonance theory. More recently, Parisi and collaborators discovered topological interactions in collective bird motion, a new paradigm of animal behaviour. The intriguing question remains whether RSB does survive beyond the mean-field limit. Numerical tests of RSB in finite dimensions have benefited from parallelized computer building by Cabibbo-Parisi's APE group. The Italo-Spanish collaboration led by Marinari and Fernandez, and elegant numerical work by Palassini and Young has accumulated evidence of a divergent correlation length and RSB in finite-dimensional spin-glasses. Parisi's work has also inspired the random first-order theory by Kirkpatrick, Thirumalai, and Wolynes, developed in the late '80s to study structural glasses and protein folding. RSB has also led Crisanti, Cugliandolo, Franz, and Kurchan to discover violations of the fluctuation-dissipation theorem and physical aging in spin-glass dynamics. I fondly remember my Ph.D. and postdoctoral years in Rome with him at the beginning of the '90s, I always admired his humanity and generosity. Together with Marinari and Parisi, we demonstrated that disorder and RSB are dynamically self-generated in structural glasses, extending SG theory to complex non-disordered systems. The beauty and vast applicability domain of SG theory make it one of the most revolutionary theories in modern physics. Regarding experiments, the evidence of RSB is still controversial. Intensity pattern profiles generated with random lasers have been shown to produce RSB-like patterns, and recent applications of RSB to hard spheres systems show jamming transitions with remarkable RSB features. We must still wait seeing RSB emerge in future experiments. Many important discoveries in theoretical physics have had to wait for decades until being experimentally demonstrated (*e.g.*, gravitational waves and black holes), and RSB might not be different. ■

In memoriam
Sir Arnold Wolfendale (1927-2020)

Arnold passed away a year ago in December 2020, aged 93. He was President of the European Physical Society from 1999 to 2001.

For half a century he was a charismatic leader in astrophysics, usually in pursuit of cosmic rays at very high energies. The Nobel Prize winner Patrick Blackett pointed him towards this field: he pursued it with great conviction, living long enough to see astrophysics develop into one of our greatest cultural assets. His own achievements brought many honours, including Fellowship of the Royal Society and the title of astronomer royal, as well as major prizes. Not only an outstanding physicist, Arnold was also an inspirational teacher to generations of students at Durham University and an engaged lecturer to the general public.



In 2008, as EPS celebrated its 40th anniversary all former presidents were asked to provide their personal memories of their terms within EPS. In the EPN39-5 issue[1] Arnold made a quick review of his presidency, reporting on the Malvern Seminar in September 1999 and on the different position papers published at the time on topics like 'The Brain Drain', 'Nuclear Energy', 'Public Awareness', 'The funding of Physics'.… He strongly encouraged links to Central and Eastern Europe by visiting several groups of physicists and politicians in Romania, Lithuania, Croatia, Albania, Serbia and Germany. He was also much involved in a project aiming to distribute posters describing the lives of famous European Physicists to school pupils.

He was indeed much devoted to outreach and the public recognition of science. Hence he arranged for a plaque to be placed in Westminster Abbey, in honour of John Harrison, whose clock-making prowess solved the problem of determining longitude.

As befits his subject, he had an international outlook, fostering links in many countries. He was instrumental in founding the European Cosmic Ray Symposium. But he remained a quintessential Englishman, proud of his standing and delighted by every invitation to give a conference address or – better still – an after-dinner speech. These perorations were delivered with great panache - he kept a joke book for the purpose. He enjoyed a rejoinder from the Lord Mayor of Dublin at a reception for the EPS Council, when he claimed as an ancestor Sir Robert Peel, founder of the English police force.

He enquired: "We call them "Peelers" – do you?" *Not anymore*, replied the Mayor, to general applause.

We will remember with affection the twinkle in his eyes. ■

[1] https://cdn.ymaws.com/www.eps.org/resource/resmgr/about_us/eps_40_years_d_weaire_and_a_.pdf

The European Physical Society is pleased to announce the first edition of The EPS Forum

Planned as a regular event, this new initiative will provide a showcase for the EPS and its activities, as well as for the activities of its Member Societies, Divisions and Groups, and Action Committees. The Forum will attract new members. It will involve the EPS Associate Members through a "Physics meets Industry" event and will also offer reviews of the latest developments in selected fields of physics research.

The EPS Forum will bring together representatives of the 42 National Member Societies, 18 Divisions and Groups and 40 Associate Members. This year it will be held from Thursday 2 June to Saturday 4 June 2022 at the International Conference Centre of Sorbonne University, Paris, France.

This three-day meeting should gather 500 participants including a majority of PhD students, Post-Docs and early-career researchers who will be introduced to exciting research opportunities in large companies and start-ups. The scientific topics addressed during the 2022 EPS Forum will be condensed matter physics, energy and sustainability, transportation and technology, accelerators, high-energy particle physics, nuclear physics, quantum technologies and photonics, machine learning and artificial intelligence, biophysics, sequencing of proteins, pandemics and cancer treatments.

The first day will be dedicated to the employment of young physicists and favour fruitful exchanges with major physics-based industrial companies. The second day will host a scientific colloquium. Recent achievements in science will be addressed by the best physicists in Europe and beyond, while round tables will discuss societal issues and best practices between the EPS Member Societies. The third day will be the regular business meeting of the EPS Council.

Already 30 large industrial groups, medium and small-sized companies and leading start-ups have responded positively to our invitation, including Thales Alenia Space, Airbus-France, Euclid Consortium, ELI Beamlines, CERN, GSI-Darmstadt, IBA, AGS Superconductor, COSYLAB, TRUMPF, IBM, Zeiss and Quandela.

Professors Barry Barish (Caltech, USA), Serge Haroche (Collège de France, Paris) and John M. Kosterlitz (Brown University, USA), laureates of the Nobel Prize in Physics, have also agreed to participate in this event. Ms. Mariya Gabriel, European Commissioner for Innovation, Research, Culture, Education and Youth as well as Prof. Maria Leptin, the new president of the European Research Council (ERC), have been invited and they have tentatively agreed to deliver presentations during our event.

The EPS Forum will bring new impetus to the EPS and its activities, and will enhance our visibility and impact. More information is detailed on the website: https://www.epsforum.org/. The Forum meets a number of priorities for all EPS Members. So, rendez-vous in Paris between 2 and 4 June 2022! ■

APS – ICTP – EPS
Travel award fellowship program

The American Physical Society (APS), the International Centre for Theoretical Physics (ICTP) and the European Physical Society (EPS) are pleased to announce the creation of the Joint APS - ICTP - EPS Travel Award Fellowship Programme as part of their activities to support the International Year of Basic Sciences for Sustainable Development (IYBSSD) in 2022. Visit the website of ICTP to find the details of IYBSSD 2022.

The ICTP, based in Trieste, Italy, has established a program specifically designed for wider collaboration with external partners: The International Training and Research (INTR) Programme. INTR provides the opportunity for active early career scientists from developing countries to reinforce, renew, or in extraordinary cases, create scientific collaborations by providing grants for short-term research visits to participating laboratories in all of Europe and North America.

A unique feature of INTR allows multiple stakeholders to join forces with ICTP to ensure the success of these visits. In cooperation with the APS and the EPS, a dedicated and more specialised framework has been created to facilitate the return of early career scientists to universities and research centres where they had previously obtained their Ph.D., known as the **Joint APS-ICTP-EPS Travel Award Fellowship Programme**. This program enables selected recipients from developing countries to return to the laboratories of their 'Alma Mater' institution and to use laboratory facilities which may not be available in their home country. This would strengthen the recipient's opportunities to conduct world-class research and increase their list of publications. In addition, through ICTP, the recipients would gain training on writing grant proposals which would enable access to research opportunities after returning to their home laboratories.

IYBSSD2022
International Year of Basic Sciences for Sustainable Development

▾ Laboratory insecticide resistance test, Montpellier. © IYBSSD 2022 IRD/P. Landmann

The Joint APS-ICTP-EPS Travel Award Fellowship Programme is open to currently active early career physicists (within 10 years of their Ph.D), with good publication records or equivalent, who are nationals of developing countries and who are currently studying or working in their same or another developing country. The period of the stay is 2 months. The Travel Award Fellowship is USD 5,000, and will be used to cover travel and living allowance.

The programme will begin in earnest with a three year pilot in 2022. The ICTP, the APS, and the EPS have pledged to contribute USD 5000 for 3 years, to fund up to 3 travel grants per year. Details on how to apply can be found here: https://www.ictp.it/programmes/career-development.aspx#anchor_25876. ■

"From PhD to CEO" meeting Europe's founders

Richard Zeltner[1], Claus Roll[2] and Yann Amouroux[2]
[1] EPS YM Action Committee – [2] Directors Europe at Optica

For the webinar series "From PhD to CEO" the Young Minds Programme of the European Physical Society (EPS YM) and the European office of the Optica (formerly OSA) invited six early-career researchers from Europe to share their experiences when starting up a business. Richard Zeltner, Claus Roll, and Yann Amouroux reflect on it and give an outlook on what is planned next.

How did the idea and the collaboration between Optica and EPS came up?

Richard Zeltner (RZ): "One of the goals for my tenure as YM chair is to encourage more industry-related activity within YM. Ever since my time as a PhD student I have an interest in the processes of transferring research into products and setting up a company. I realised that if this is something I am interested in, it might be of interest for others as well. This is how the idea was born. Considering the strong photonics industry in Europe, six early-career researchers from Europe were ● ● ●

"From PhD to CEO" featured photonic entrepreneurs from Ireland, Germany, Spain and Portugal

invited to share their experiences when starting up a business. Having a personal connection to Optica, and considering its status as a leading professional society, seeking partnership was only natural to increase the series` visibility and to serve the overall community as well as possible. This is where Yann and Claus came into play."

Yann Amouroux (YA): "The connection with Richard existed prior to his election as EPS YM Chair, we met in July 2018 via Optica Student Chapter & YM section based in Erlangen and kept in touch ever since. It was a natural development and a great opportunity for all of us to work together on this project."

Claus Roll (CR): "When Richard contacted us with this idea, we were confident in its success. Similar to Optica webinar series "Navigating Graduate School Abroad" started previously it addresses practical questions from master students, PhD students as well as postdocs who in these times of access and travel limitations needed information and support for the next steps in their careers."

How were young entrepreneurs invited?

RZ: "To ensure that the series is interesting for a broad audience we invited speakers with various technological backgrounds, ranging from biophotonics to quantum technologies. This was likely a key success factor for the series. Aligned with the vision of EPS we also aimed for representation from different regions and countries, and for gender parity in the speaker list, which was achieved."

CR: "In general, the speakers were from various backgrounds, showcasing the multiple situations a founder is confronted with, such as the business idea, the sector, the investors, different regulatory situations and rules across European countries, as well as personal backgrounds. Following these considerations, we identified potential candidates in our own networks and reached out to them to start a discussion."

How did the invitees react?

YA: "Nowadays people get invited to so many online events that it was important to convey our message carefully, highlighting why we are convinced about the relevance and future success of "From PhD to CEO". With almost 100 % of the people coming back with an immediate "yes", we apparently did a good job in doing so. After learning what the series is about they were all super happy to be involved."

What were the highlights in the series?

CR: "Strikingly speaking none of the webinars were identical, neither in content, nor in format. This was an extremely positive surprise to us. Another highlight was the fact that our audience came from all over the globe, with questions about all kinds of topics, from business ideas, via funding to what the job looks like, and many more."

YA: "The variety in the talks: everyone had a very different route to where they are now and, depending on the country of origin, different opportunities provided to them. The series told us how student intellectual property is handled in some countries compared to others and how motivation, belief and aspirations can lead to extraordinary results. Not all ventures are successful but all our speakers are doing very well and we hope the series might encourage others to start their own business."

Are you happy about the outcome?

YA: "We had hundreds of attendees from all over the world, many of them students or early-career professionals. The series targeted that group and we got them engaged. We were also extremely happy to see that about 1/3 of the delegates were women, a high rate that might be attributed to the gender parity in the speaker list. We will certainly work towards encouraging diversity in our second series as well. So yes, we were all pretty happy with the outcome."

What is next?

RZ: "In view of the series' success, the feedback from both speakers and our communities, and how smooth the collaboration went, it is natural to consider a second edition. With the current EPS presidency putting a higher emphasis on the relations to industry and related activities, it will also fit very nicely into the overall roadmap of EPS. An even stronger promotion within the EPS network and its coming events involving the private sector is planned."

CR: "We had a first meeting to start the preparations and are currently discussing the next round of invitations. While the still rather unpredictable pandemic situation makes planning difficult, we also had a discussion on transferring the format from the virtual into the physical realm, *e.g.*, in the context of conferences or larger meetings."

YA: "A focus in the second series will be to maintain high diversity in the speaker list and to include countries that have not been represented yet. Really looking forward to this new series later in 2021!" ■

"We had hundreds of attendees from all over the world, many of them students or early-career professionals. The series targeted that group and we got them engaged. We were also extremely happy to see that about 1/3 of the delegates were women, a high rate that might be attributed to the gender parity in the speaker list."

[EDITORIAL SPECIAL ISSUE]

Research for the energy transition

This EPN special issue on research for the energy transition comes at a crucial time, on the heels of the G20 Heads of State and Government Summit in Rome (30-31 October 2021) and of the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow (31 October – 12 November 2021). Both events, where all parties acknowledged the close link between climate and energy, aimed at strengthening the commitments in reducing greenhouse gas emission intensity, as part of mitigation efforts, on the shortest possible time scale. As most of the world greenhouse emissions are produced by the energy sector, the impact of decarbonisation of the energy sector on climate change is going to be significant. The present special issue is addressing the question of how research in energy technologies is playing a major role to support the energy transition.

The recently proposed *IEA Net zero emission by 2050* scenario[2] foresees a substantial increase in renewable energy sources covering 2/3 of the energy supply in 2050, a doubling of the present nuclear power generation and the reduction of fossil fuels from 80% in 2020 to 20% in 2050 with a massive use of carbon sequestration and storage. This scenario is setting formidable challenges to the development of the energy sector. The advances in conversion efficiency of photovoltaic cells and the diffusion of wind farms have been significant. Nevertheless, the massive use of renewable energy sources has to deal with their intermittent nature, and requires large scale electricity storage technologies and a substantial adaptation of the electricity grid. On a longer time scale, the use of fusion energy may provide a baseload electricity source carbon free and virtually unlimited provided all the related challenges are satisfactorily overcome.

The contributions in this special issue are devoted to these challenges. They are written by predominantly young specialists, directly involved in specific studies. Topical subjects have been selected, starting with the development of efficient perovskite solar mini modules. The problem of atmospheric flows in large wind farms is addressed, as well as that of the lifetime of components in a fusion reactor. Promising solid-state batteries are presented and discussed and the challenge of future electricity grids and of digital grids beyond smart grids is addressed. Of course, this list of subjects is far from being exhaustive, but it can provide, at a glance, a panorama of the current trend in energy technologies to cope with the "desperately sought" energy transition.

The solution will not come from a single technology but rather from a portfolio of technologies in which renewables will have a major role but other technologies will be necessary. Our collective responsibility as physicists is to ensure that the basic understanding of the whole energy field is made available to our society. ■

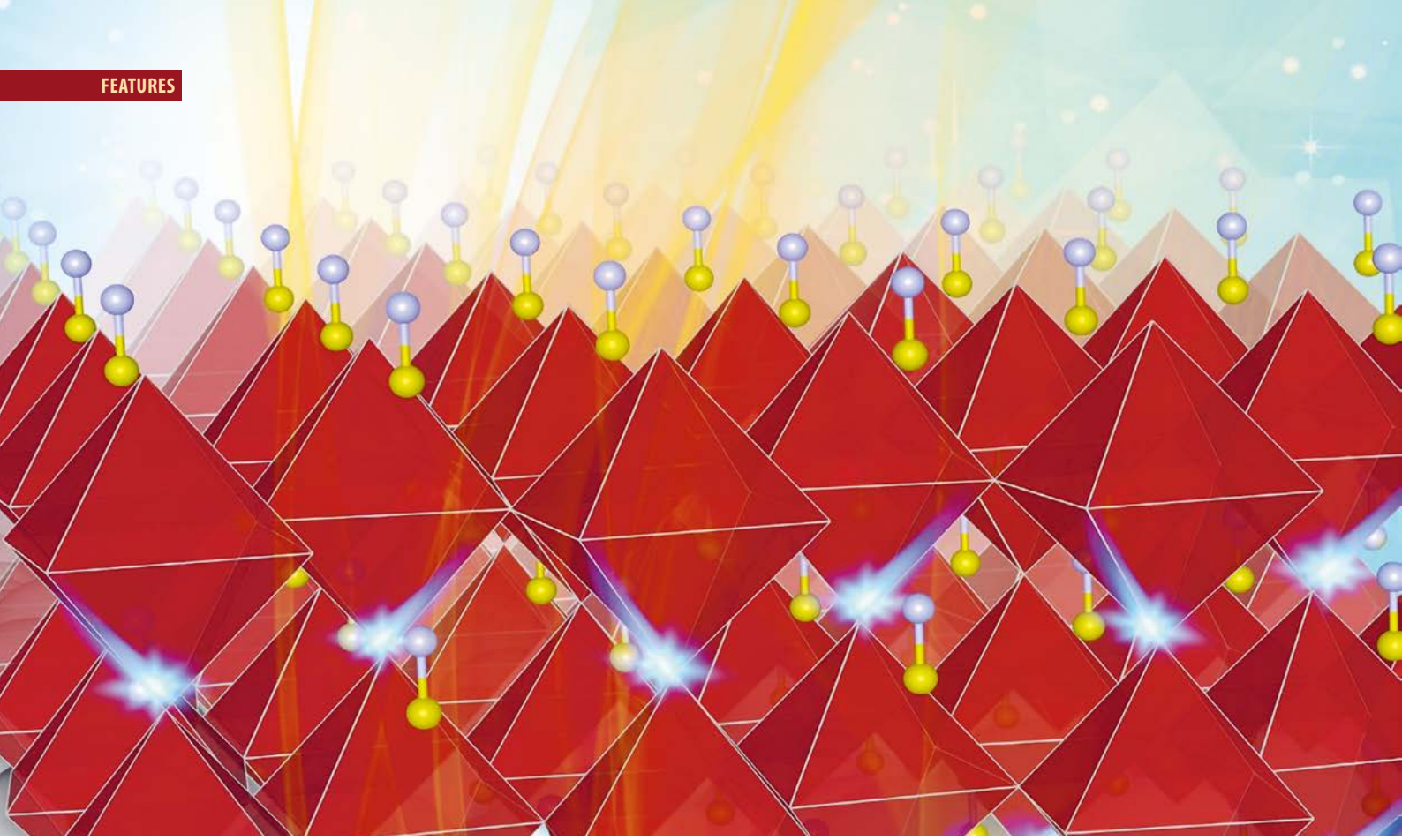
Luisa Cifarelli,
University of Bologna
Francesco Romanelli,
University of Rome Tor Vergata
Directors, Joint EPS-SIF International School on Energy

THANK YOU!

The EPN Editors are very grateful to Luisa Cifarelli and Francesco Romanelli, who as Guest Editors created an attractive and timely special issue about research for the energy transition, with excellent contributions by the authors. We highly appreciate your work and endeavour for EPN. Thanks a lot to all of you!

[1] PCC Report, https://science2017.globalchange.gov/chapter/2/

[2] https://www.iea.org/reports/net-zero-by-2050



PEROVSKITE SOLAR MINI-MODULES

Annalisa Bruno – DOI: https://doi.org/10.1051/epn/2021501
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In the last decade perovskite solar cells have shown remarkable improvements in power conversion efficiency which have driven the interest to commercialise the perovskite technology. Here, I will present an overview of our recent works focused on the development and the understanding of highly efficient co-evaporated perovskite solar cells with excellent thermal stability and remarkable upscalability. Our works demonstrate the compatibility of perovskite technology with consolidated industrial processes and its potential for next-generation photovoltaics on the market

Undertaking the considerable decarbonisation imposed by the Paris Climate Agreement while meeting the ever-increasing energy demands, requires disruptive progress in renewable energy. Given the enormous solar irradiance received on Earth photovoltaics is one of the most appealing options to meet the immediate needs as a cost-competitive alternative to the fossil fuels-generated electricity. Recently, metal-halide perovskites have emerged as one of the most promising low-cost photovoltaic and optoelectronic technologies. Their excellent optoelectronic properties and their versatility in producing high-quality thin films are the key aspects to drive this technology. The power conversion efficiencies of perovskite solar cells have reached 25.5%[1] over small areas in just a decade using lab-scale solution processes. Unfortunately, these methods are not easily transferable to the fabrication of perovskite solar modules which are necessary for real-life applications. Processing of the active materials with a coating technique already established in the semiconductor industry can guarantee a fast market entry for the perovskite technology.

▲ Artist's impression of a perovskite solar mini-module

[1] https://www.nrel.gov/pv/cell-efficiency.html

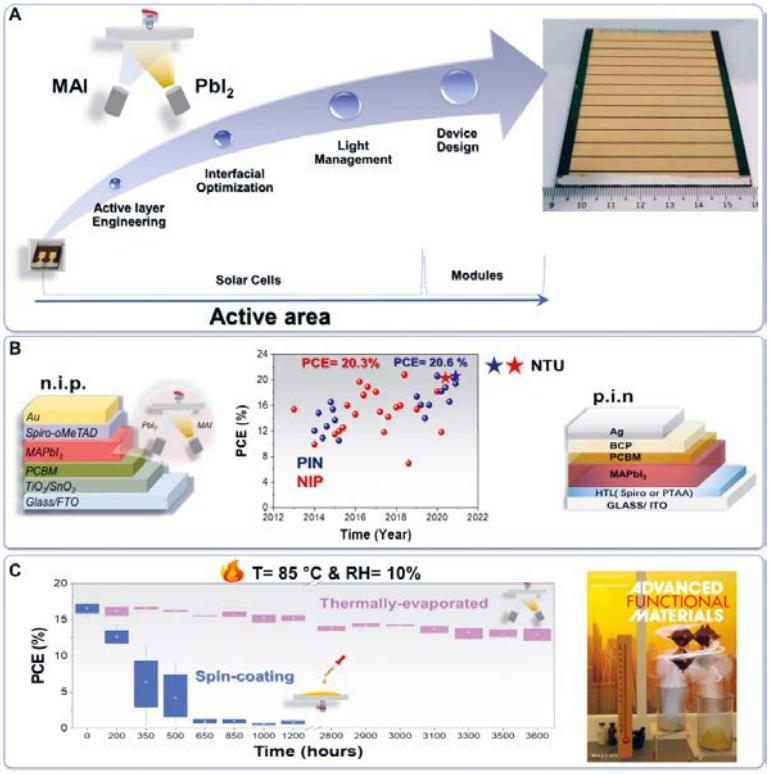
Co-evaporation technique

Co-evaporation, widely used for organic light-emitting diodes in displays, is a vacuum-based industrial-scalable method allowing the sequential deposition of functional materials to form multi-layered architectures. The method offers multiple advantages over the solution-processed counterparts such as a high purity of the sublimed materials, the precise control of the film thickness, and the elimination of toxic solvents. Previously, various groups around the world have demonstrated the feasibility of co-evaporated small areas (~0.1 cm^2) perovskite solar cells with power conversion efficiencies varying from 15 to 20%, and with different perovskite compositions [1,2]. In this work, we present our recent results on how a combined customisation approach of the co-evaporation perovskite process and the architectures of the perovskite solar cells allowed to maximise power conversions efficiencies for co-evaporated MAPbI3 perovskite solar cells in both n-i-p [3-4] and p-i-n [5] configurations[2] with minimal losses when the active areas are scaled-up with remarkable intrinsic stability. We also show that the optimised device architecture is transferable from lab-scale prototypes to mini perovskite solar modules achieving power conversion efficiencies above 18% [3-4]. In addition, for the first time we show that the same architecture can be directly used for coloured semi-transparent perovskite solar cells and modules [3]. The scalability and versatility of the co-evaporation process are critical features to reach the industrial standard for the commercialisation of perovskite technology.

Production of perovskite solar *cells*

The co-evaporation deposition takes place in intrinsically clean high-vacuum environments and its intrinsic scalability is related just to the geometry and the design of the instrument. Our roadmap to reaching high power conversion efficiency over large areas is schematised in Figure 1A. It includes two main steps. The first step involves the optimisation of a small area perovskite solar cell through a combined methodology of active layer engineering, interfacial optimisation, and light management. The second step focuses on the design of a perovskite solar *module* by combining perovskite solar *cells* in series with specific shapes and distances to maximise the covered area and minimise the sheet resistance of the transparent conductive oxides substrate of the module. The optimisation strategies specific for co-evaporated n-i-p [4-6] and p-i-n [7] architectures allowed us to reach among the highest power conversion efficiencies for both configurations in small area perovskite solar cells (Figure 1B) [4].

Moreover, we have shown for the first time that the co-evaporated MAPbI3 thin films and perovskite solar cells have remarkable thermal stability (over 5 months at high temperature), even without any advanced modification or additional encapsulation (Figure 1C) [6]. Such excellent thermal stability is driven by the low-temperature growth process leading to tensile-stress-free and compact films with outstanding interface robustness which makes the co-evaporated $MAPbI_3$ intrinsically stable. It represents a breakthrough for the pure-MA-containing[3] perovskite solar cells, which have always been suffering from fast degradation. These results highlight that the growth process is critical to driving the properties of perovskites well beyond their existing limits. The approach has the potential to drastically change the way we look at the interplay between perovskite composition and the growth process towards their long-term stability [6].



▲ **FIG 1:** Co-evaporated Perovskite Solar Cells. A. Development roadmap toward high efficiency co-evaporated perovskite solar cells. B. co-evaporated power conversion efficiencies (PCEs) versus time for both n.i.p and p.i.n architectures. C. PCE as a function of time under thermal aging at 85 °C and 10 % Relative Humidity (RH) of co-evaporated MAPbI3 (pink) and spin-coated perovkite solar cells from FAMAC (blue) (Reprinted from [6]; Copyright 2017 Wiley-VCH Verlag GmbH & Co. KGaA).

Production of solar *modules*

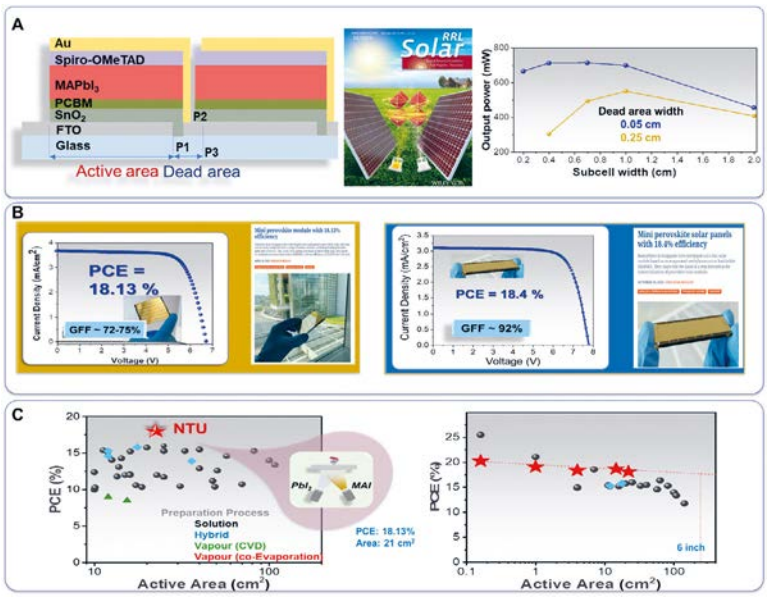
When the active areas of the optimised perovskite solar cells was scaled up from 0.16 cm^2 to 4 cm^2 the power conversion efficiencies dropped by about 2%, mainly due to a decrease in fill factor (FF)[4] ●●●

[2] n-i-p and p-i-n refers to the stacking order of the material layers in the solar cell.

[3] Methylammonium, MA.

[4] The fill factor (FF) is a parameter that determines the maximum power from a solar cell. It is the ratio of the actual maximum obtainable power to the product of the open-circuit voltage and short-circuit current.

ascribable to the high resistance of the transparent conductive oxides, while preserving the good quality and high uniformity of the co-evaporated $MAPbI_3$ over large areas [3-4]. To minimise the fill factor loss while moving towards large-area solar devices, we implemented a mini perovskite solar module by connecting thin strips of the cells in series (Figure 2A). The serial connection is enabled by multiple scribing (known as P1, P2, and P3) on the perovskite solar modules, resulting in optical losses due to inactive areas. The geometrical fill factor (GFF) represents the ratio between the surface of the active area and that of the panel [4]. We have used both mixed mechanical and laser etching (MLE) and fully laser-etched (FLE) methods to minimise the inactive areas. In the modules made with MLE the width of the dead area was around 0.25 cm while in module constructed using FLE it was reduced to 0.05 cm. The sizes of the sub-cells were adjusted to maximise the outpower according to the modelling reported in Figure 2A. The optimised MLE-made modules with an active area of 21 achieved a record power conversion efficiency of 18.13% with a geometric fill factor (GFF) of 72% while the FLE-made modules achieved a power conversions efficiency of 18.4% with a GFF of 91% (Figure 2B) [4-6]These values were the highest reported, at the date of publication, for perovskite solar modules fabricated with any deposition technique. The results prove the excellent scalability of the co-evaporation process which guaranteed minimal conversion losses when the sizes are scaled-up (Figure 2C) [3].



▲ **FIG 2: A. Architecture of co-evaporated Perovskite Solar Modules (PSMs) and the output power of the modules as a function of the size of the sub-cells in the architecture for different sizes of dead areas. B. Champion perovskite solar modules, photovoltaic curves and power conversion efficiencies [4][6]. C. Power conversion efficiencies of perovskite solar modules with an active area larger than 10 cm² fabricated with different deposition methods and PCEs record values for each active area in the range from1 cm² to 200 cm² [3]. (Reprinted from [4] Copyright 2017 Wiley-VCH Verlag GmbH & Co. KGaA and [3] Copyright Cell Press.)**

Coloured cells and modules

Semi-transparent perovskite solar cells have shown potentials as building-integrated photovoltaics and to be integrated into multi-layered high-efficiency tandem solar cells. We have fabricated semi-transparent perovskite solar modules and solar cells using the same device architecture as the one used for opaque ones, except that the gold electrode was substituted with a semi-transparent electrode including a 1 nm Ag and an Indium Tin Oxide (ITO) layer [3]. This resulted in colourful co-evaporated solar cells by tuning the thickness of the ITO electrode which modifies the reflection peak of the semi-transparent cells, thus creating distinctive colourful hues across the entire visible spectrum (Figure 3A). This approach of tuning the transparent electrode thickness is the simplest and most effective way to tune colour without introducing additional layers and/or fabrication processes [3]. While maintaining a high power conversion efficiency, changing the colour of the semi-transparent cell colour can be challenging since light loss due to colour reflection and series resistance increase in ITO electrodes is challenging. In our work varying the ITO thickness, the perovskite solar cells show consistent power conversion efficiencies of around 16% for all the colours created (Figure 3B) [4]. Using the same architecture, semi-tranparent perovskite solar modules with different colours and power conversion efficiencies above 11% have been realised (Figure 3C).

Towards commercial production

We have shown that a combined effort on active layer engineering, interfacial optimisation, and optical management allowed us to demonstrate the feasibility of small area co-evaporated MAPbI3 perovskite solar cells achieving power conversion efficiencies well above 20% in both n-i-p and p-i-n configurations and remarkable thermal stability. Moreover, we have translated the optimised architecture together with a module design customised to the etching procedure to demonstrate the feasibility of producing perovskite solar modules with power conversion effiency above 18% and a geometric fill factor up to 91%. The same optimised architecture has been adapted to realise colourful semi-transparent perovskite solar cells and modules which can deliver consistently high power conversion efficiencies for a wide range of colours. In summary, the versatility of the co-evaporation method, together with the high efficiency and remarkable stability of the perovskite solar cells brings the commercialisation of perovskite technology one step closer. ■

About the author

Annalisa Bruno is Principal Scientist at the Energy Research Institute @Nanyang Technological University, (ERI@N of NTU) and at the Italian National Agency for New Technologies, working on hybrid materials for energy technologies. Earlier, she worked at Imperial College London. She received her B.S., M.S. and Ph.D. Degrees in Physics from the University of Naples Federico II, Italy. annalisa@ntu.edu.sg

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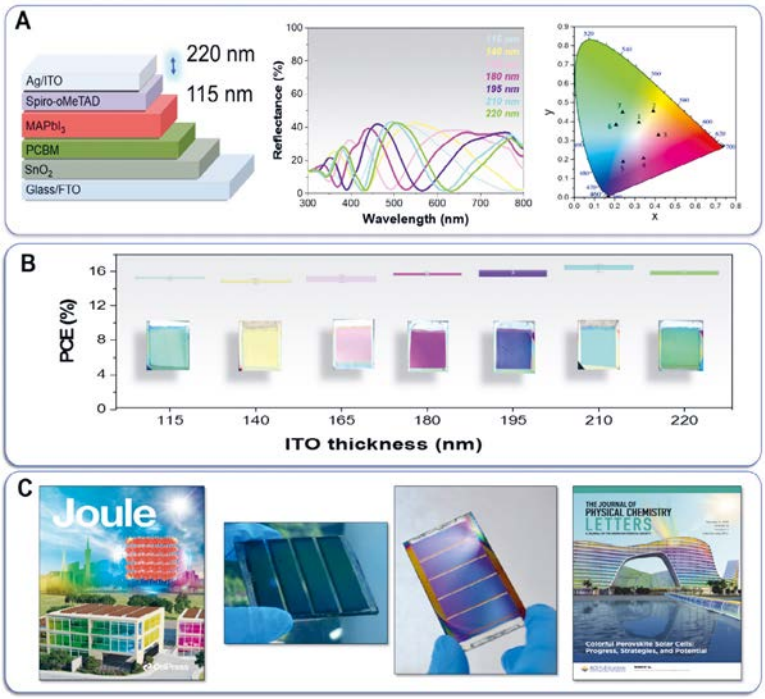

▲ **FIG 3:** Coloured co-evaporated perovskite solar cells and modules. A. Image of a 16 cm² active area SnO_2 based semi-transparent perovskite solar module consisting of series-connected 4 sub-cells. (b) Dark, forward and backward J–V curves of a transparent perovskite solar module. B. Power conversion efficiency of semi-transparant perovskite solar cells as a function of the electrode thickness, determining the colour appearance of the perovkite solar cell [4]. C. Photographs of the coloured semi-transparent perovskite solar modules and journal that covered highlighting their results [7]. (Reprinted from [4]. Copyright Cell Press and [7]. Copyright from ACS Publications.)

ATMOSPHERIC FLOWS IN LARGE WIND FARMS

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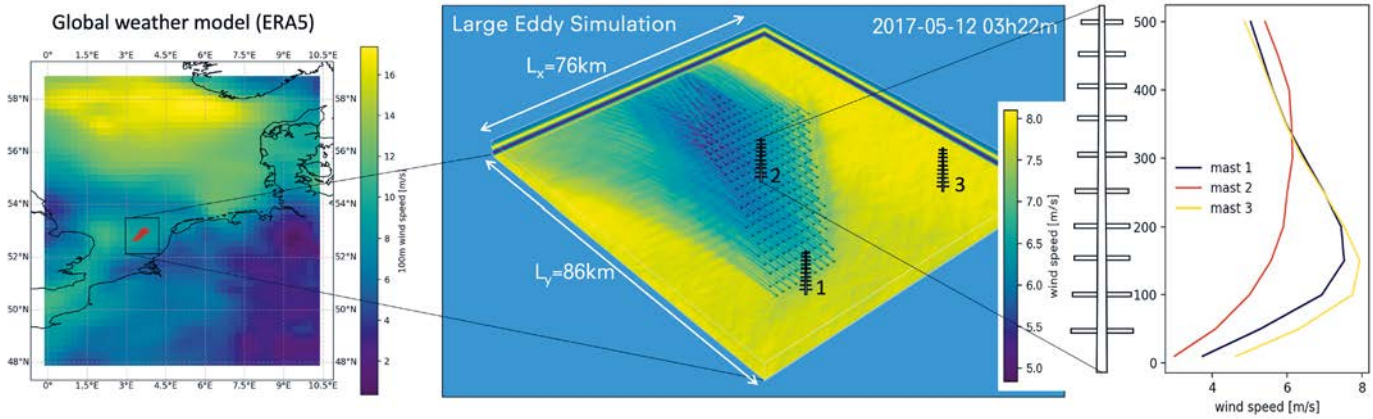
As we are transitioning to an energy system based on renewable sources, the atmosphere is becoming one of our primary energy sources. Understanding atmospheric flows through wind farms has become an issue of large economic and societal concern.

Two characteristics of renewable energy sources make them difficult to integrate in our power system: variability and unpredictability. Variability refers to their fluctuating output in concert with weather systems. These fluctuations cover a range of time scales from years to sub-seconds. Unpredictability means that, unlike conventional power plants, the output of renewable energy sources cannot be predicted exactly; neither in the short-term (hours to days ahead) nor in a climatological sense in the long-term (over multiple years). The intermittency of renewable energy sources requires a certain amount of flexible resources like energy storage or back-up power plants to accompany the build-out of wind and solar farms. However, such technical solutions are costly and better knowledge of the atmospheric conditions that drive power production can avoid such investments to some extent. In this article we highlight some aspects related to modelling the flow and power production of the new generation of wind farms. These have rapidly become much larger, growing from 500 MW 10 years ago to 1500 MW today and expected to reach the 4000 MW mark by 2025.

▲ A view on the Borssele Offshore Wind Farm Zone.



▲ **FIG. 1:** Left: snapshots of wind speed at 100m height over the North Sea as modeled by ERA5 (the ECMWF 5th Generation of the atmospheric reanalysis of the global climate covering the period from January 1950 to present). Middle: Large-Eddy Simulation driven by ERA5 of the planned IJmuiden Ver 4GW wind farm. Individual turbines are visualised with black dots. Right: Vertical profiles of wind speed for three virtual met-mast locations.

Predicting the yield of wind farms

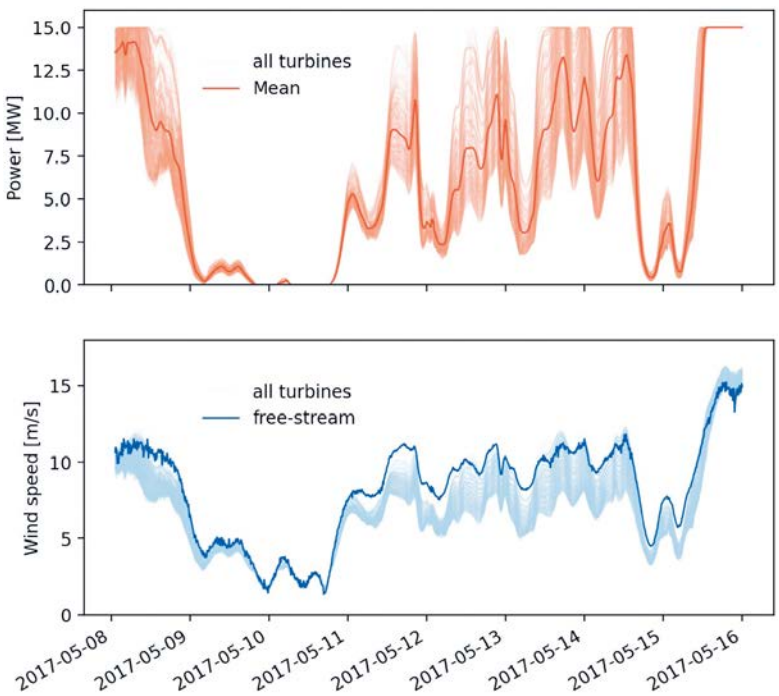
The first step in modelling the expected production of a wind farm is to characterise the wind climate in absence of the wind farm, sometimes referred to as *free-stream wind*. To this end, local wind measurements are complemented with the output of numerical weather prediction models and micro-models to obtain a climatological "wind speed map" over the site. Especially for wind farms in complex environments (*e.g.* in forests, mountainous terrain or close to other wind farms), the wind speed can have strong local variations and the micro-model is an essential step.

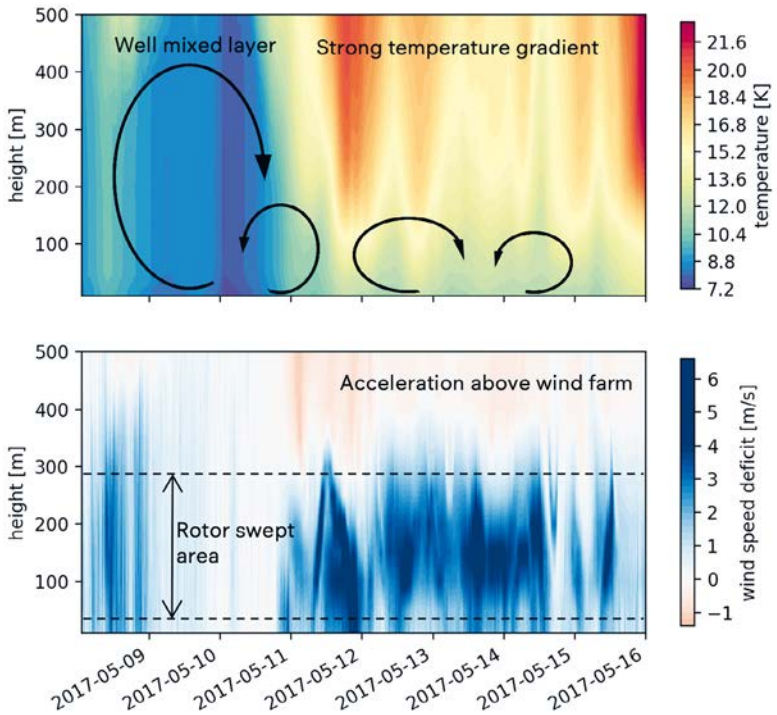
The second important step is predicting how the wind turbines themselves interact with the flow inside the wind farm. Wind turbines have been designed with an important objective: extracting kinetic energy from the atmosphere and converting it to electrical energy. They are very efficient in doing this and so behind a wind turbine there is a wake region with a significant reduction in wind speed. Models of different complexity to predict wind farm wake losses exist, from simple engineering or analytical models to more complex computational fluid dynamics models. When applying these wake models, the free-stream wind as described above is used as input for the wake models. The large-scale flow is thus assumed to be independent of the flow inside the farm. However, this is becoming a problematic assumption, especially for the new generation of wind farms, which are becoming ever larger and built more closely together. One of the challenges in understanding wind farm flow physics is the coupling between the micro-scale (say, turbine level ~100 m) and the mesoscale (100 km or more) which is relevant for atmospheric processes [1].

Large-Eddy Simulation

Large-Eddy Simulation (LES) is a computational technique that has been successfully applied in both wind energy science and atmospheric physics. The essence is to numerically integrate the filtered conservation equations for momentum, mass, temperature and moisture on a grid that is fine enough to capture the largest part of the turbulent spectrum. In this way, turbulence is explicitly simulated, rather than parameterised. Atmospheric LES codes also include processes like radiation, cloud thermodynamics and the land- or sea-atmosphere interactions. Wind turbines can be represented as semi-permeable rotating disks that exert wind speed dependent forces on the flow. LES thus provides a unified framework to capture wind farm flows and windfarm atmosphere interactions in a single model. Its large computational costs have long been considered as a barrier for practical applications, but innovations in computer science, *e.g.* exploiting Graphics Processing Units, have moved LES to the frontier of models for the wind energy industry [2, 3, 4].

▼ **FIG. 2:** Eight day time series of the modeled turbine power and wind speed in the IJmuiden Ver 4GW wind farm. Top: all individual turbine powers and turbine average power. Bottom: hub height wind speed at all turbines and free-stream wind speed.





▲ FIG. 3: Temperature profile over time (top) and velocity deficit in the middle of the wind farm (bottom).

Large wind farm physics at the frontier of flow modelling

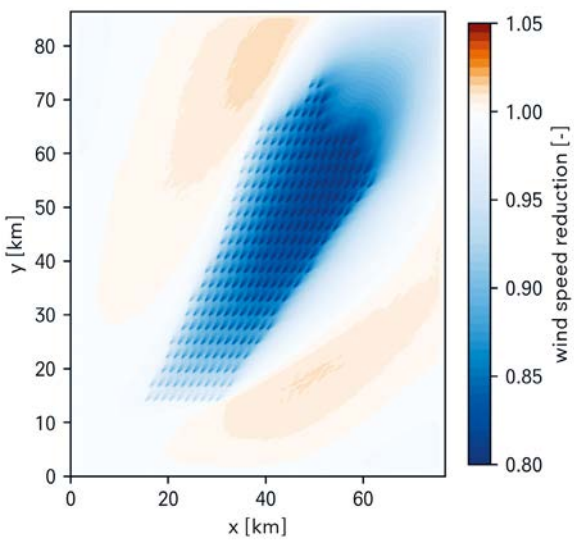
To illustrate some of the issues surrounding wind farm yield predictions, we present results of an atmospheric LES encompassing a large (100 km^2) wind farm. A year-long atmospheric LES driven with large-scale boundary conditions from the ERA5 [5] according to a setting described in [4] has been performed. The simulation domain covers 76.8 km by 86.4 km and is 4 km high with a horizontal resolution of 100 m and a vertical resolution of 25 m. A total of 275 turbines of the IEA-15 MW reference turbine [6] type was included on the location of the IJmuiden-Ver wind farm zone that is currently being prepared for tendering. Large-scale wind fields as well as detailed LES wind fields are shown in figure 1 for a day with strong wake effects. A time series of 8 days of the power production and wind speed per turbine are shown in figure 2. The figure exposes how difficult it is to predict wind farm production: huge swings in power output over short time intervals, a spread of more than 50% between first row and fully waked turbines inside the farm on a given time, days of practically zero production followed by full 4 GW production. To put these numbers into perspective: the average Dutch electricity demand is around 12 GW and can be as low a 8 GW. This single large wind farm will thus intermittently cover between 0% and 50% of the total demand. Note how small free stream wind speed variations (between 8 m/s and 10 m/s) lead to differences in power output of almost 80%.

Why is it that wake effects inside the wind farm vary so much from time to time? Besides the dependence on wind speed (through the power curve) and wind direction (in relation to turbine arrangements), the vertical structure of the atmosphere is an important factor. To illustrate this, consider the vertical profiles of temperature and the wind speed deficit (reduction with respect to the free-stream wind speed) in the middle of the wind farm as shown in figure 3.

During the first few days, the atmosphere is well mixed over at least the first 500 m of the boundary layer. Around May 11th, a strong vertical temperature gradient develops, indicating a stable atmosphere in which turbulent mixing is suppressed. The wind speed decreases strongly around the rotor heights since momentum is extracted, but there is little turbulent entrainment from higher layers. Above the wind farm an increase in wind speed is visible, much like the acceleration of a stratified fluid over a small hill or obstacle.

Global blockage and far wake effects

A phenomenon that currently receives a lot of attention in the wind industry is global blockage [7]. Loosely speaking, global blockage refers to the combined induction effect that a wind farm as a whole exerts on the flow *upstream* of the wind farm. This phenomenon can be considered as a manifestation of a gravity wave, and can be understood by analogy with an object in a stream of water: through pressure forces, the fluid upstream will "feel" the obstacle and will flow around it. A deceleration in the streamwise direction combined with wave-like phenomena are the result of this balance between pressure and buoyancy forces. Upon close inspection, figure 1 shows some signatures of global blockage: on the east (right) side of the wind farm a prolonged region of lower wind speed exists. On the west (left) of the wind farm, a wave-like pattern can be observed. The vertical profile of the



▲ FIG. 4: Composite plot for all south-westerly wind directions of the velocity deficit.

southern met-mast shows a reduction in wind speed compared to the free-stream wind. A yearlong LES run provides interesting possibilities to look at flow statistics conditioned on atmospheric circumstances. For example, one could take the average wind speed deficit for all situations with south-westerly winds, shown in figure 4. Apart from the stronger wake effects deeper in the wind farm, a noteworthy feature is the acceleration of the flow alongside the wind farm. Though consistent with the interpretation of blockage as gravity waves, the existence of such accelerations is yet to be confirmed by measurement campaigns.

As favourable locations for wind energy become more crowded, the inter-wind-farm wake effects will become more prominent. Observations of wake effects extending for tens of kilometres, thereby affecting down-stream wind farms, have already been reported. Figure 4 shows that such effects are also present in the LES runs of the 4 GW wind farm. Turbulent mixing, strongly related to atmospheric stability, will determine how fast high-momentum air from higher altitudes is mixed into the wake zone. The wind energy potential of a certain region will thus ultimately be dictated by the balance between extraction of kinetic energy (converted to electricity) and the turbulent flux of kinetic energy from above.

Prospects and challenges

Despite the scientific advances that enable us to get a better grip on wind farm flow physics, some open questions remain, many of which fall in the category of wind-farm atmosphere interactions. Innovative wind farm control strategies are aimed at enhancing mixing, for example in the *helix approach* [8] where individual turbine blades are manipulated in a way that creates a helical wake zone. An unanswered question is what the limits to vertical entrainment of momentum are under control strategies aimed at increasing turbulent mixing.

Turbulence is also a critical factor in wind turbine design. Today's design practices are largely based on synthetic turbulence fields that respect some but not all turbulence characteristics. A more natural approach would be to embed an aero-elastic model directly into an LES - an avenue that is becoming feasible with today's computer power.

In the end, the entire oceanic and meteorological environment of a wind farm matters for its design. Waves, currents, turbulence, extreme gusts, icing, impacts of hydrometeors (raindrops) on blades: once built, the turbines need to withstand it all. A better understanding of these processes will bring down capital and operational costs of wind energy.

The fact that renewable energy sources are so intimately coupled to the atmosphere could well lead to a prosperous era for the atmospheric sciences. The need to transform our energy system is bringing this field to the forefront of our new industrial revolution and puts atmospheric physics for wind farms firmly on the scientific agenda. ■

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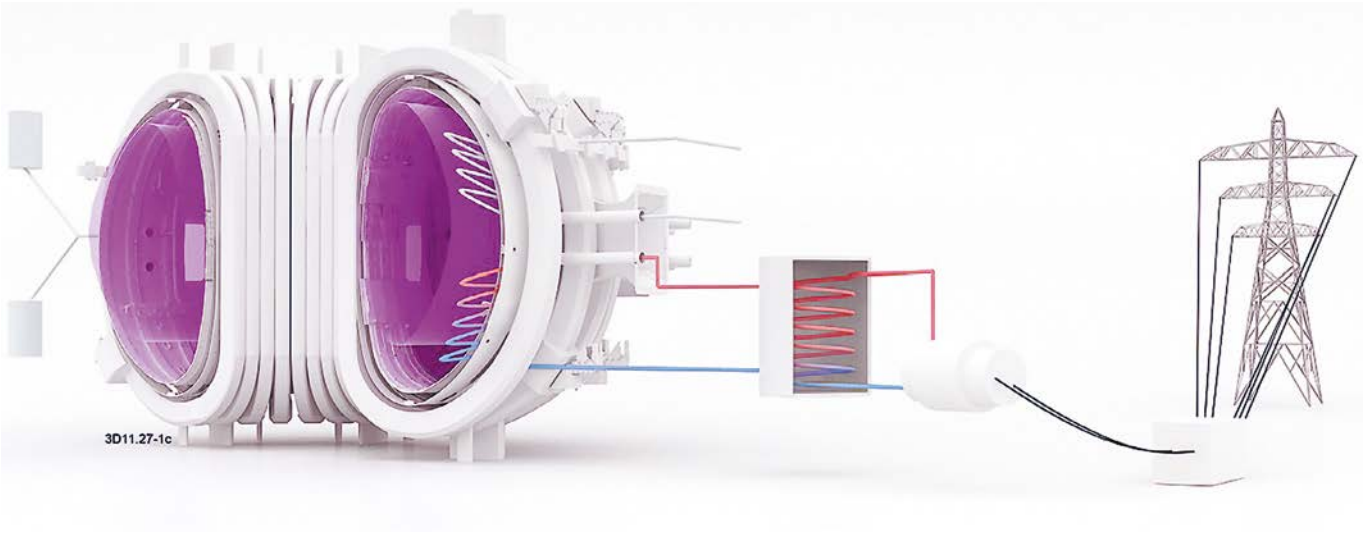

THE LIFETIME OF COMPONENTS IN A FUSION REACTOR

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Nuclear fusion is one of the most promising energy sources to satisfy our future needs. However, several open challenges are yet to be solved for the realisation of fusion electricity. Among the crucial issues, it is key to develop innovative solutions to increase the lifetime of the components inside a fusion reactor.

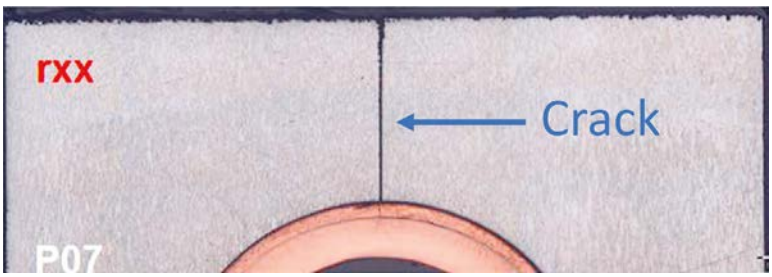
▲ Metal cooling islands on a nanoelectronic device (Nikolai Yurttagül, TU Delft)

Nuclear fusion is the reaction that keeps our Sun and the other stars burning. It occurs when two light nuclei, for example made of hydrogen isotopes, are brought sufficiently close together so that the strong nuclear force can overcome the repulsive electrostatic interaction, leading to the formation of a heavier nucleus and the release of energy. Using fusion on Earth as an energy source has been the goal of scientists from all over the world since the 1950s. Compared to other sources used for electricity production, fusion offers indeed unique advantages. Firstly, fusion is intrinsically safe since a runaway chain reaction is physically impossible inside a reactor. Moreover, the resources used as fusion fuel are available to all countries, meaning that no competition between governments would arise to ensure the supply. Most importantly, fusion benefits from a high environmental sustainability, with little to no burden left for the following generations: the fuel is virtually unlimited (available for millions of years), the amount of material resources used per TWh produced is small, no greenhouse gas is emitted during the energy production process and no long-term radioactive waste is generated. As far as waste is concerned, the reactions inside a fusion power plant would leave behind only a small amount of helium, which, being a monoatomic inert gas, is non-toxic and does not contribute to global warming. Therefore, the only waste to be managed would be due exclusively to the decommissioning of the reactor itself. The less material is needed for the overall life of the fusion plant, the less are the expenses and the environmental impact of fusion as an energy source. In this mass balance, a key role is played by the lifetime of the components operating inside a reactor, since more durable components can be substituted less frequently.

The walls of a fusion reactor

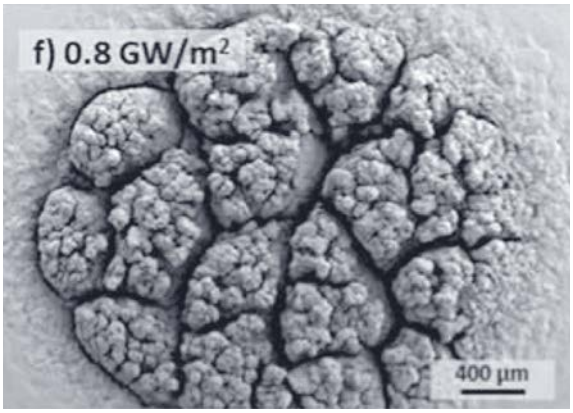
Unfortunately, coming up with a long-lasting container for a small burning star is not an easy task. The extreme environment in which a fusion reactor operates results in a combination of different loads on the walls. State-of-the-art technology and material science are simply not mature enough to deliver a component having a lifetime equal to the overall life of the fusion plant, and consequently some parts must be replaced multiple times. The damage to the components, that determines their lifetime, depends on the different depositions that the

burning plasma is applying on the walls, which consist of **heat loads**, **particle loads** and **neutrons**. The thermal energy and the particles are stopped at the wall closest to the plasma, which is covered by the so-called Plasma-Facing Components (PFCs). Neutrons, on the other hand, penetrate deeply in the machine damaging the whole volume of the reactor. Due to their location, the PFCs receive the highest damage during operation and thus these are the parts with the shortest lifetime in the reactor. In particular, they receive the thermal power that is continuously fed to the plasma to sustain the fusion reactions, the so-called plasma heating power. Due to the small heat exchange area, the heat fluxes experienced by the PFCs are extreme, starting from ~ 1 MWm^{-2} and reaching peaks of 20 MWm^{-2} in special regions. To provide an idea of the order of magnitude, this power density is comparable to the one leaving the surface of the Sun, of about 60 MWm^{-2}. Such power densities result in high temperatures and steep thermal gradients that arise inside the loaded materials, leading to thermal stresses. In the PFCs, such thermomechanical loads are the main contribution to the stresses generated during the nominal operation of the reactor, and they can lead to the mechanical failure of the component by, for example, thermal fatigue or creep-fatigue. The first phenomenon is dominated by the low-cycle fatigue, which consists of the failure of the material due to the accumulation of plastic strain. An example of such behaviour can be found in Figure 1, which shows deep cracking occurring in certain PFCs, called the divertortargets, after cyclic high heat loads [1]. The creep-fatigue is a more complex and synergistic phenomenon in which creep, that is the temperature dependent irreversible deformation of a material due to the application of a monotonic stress, interacts with the thermal fatigue resulting in the acceleration of crack growth by the accumulated creep damage especially at grain boundaries or other discontinuous locations. The heat loads we have just described are applied for a sufficient time such that the thermal equilibrium is reached inside the PFCs, which is in the order of tens of seconds. However, in addition to such fluxes, also thermal shocks can occur inside a fusion reactor. These are due to instabilities (*e.g.*, Edged localized Modes (ELMs) or Vertical Displacement Events (VDEs)) in the plasma which results in bursts of energy deposited on the wall. Since the time scales of these transients are far lower than the time scale of the thermal diffusion inside the material, only the surface layers of the PFCs will absorb all the deposited heat. Serious material degradation such as roughening or crack formation on the surface can occur, depending on the power density (which can reach ~1 GWm^{-2} for ~1 ms), as well as the base temperature of the material before the transient event. Figure 2 shows an example of the surface modification that occurs when applying multiple thermal shocks to a PFC [2]. When the heat transients are too energetic (*e.g.*, during plasma disruptions), the energy fluences are so high and the time so short that the surface layer of the PFCs instantaneously melts and, in critical regions, evaporates. Therefore, these latter events cannot be tolerated inside a reactor and reliable mechanisms of disruption prediction and mitigation are mandatory for the design of a high-power fusion plant.

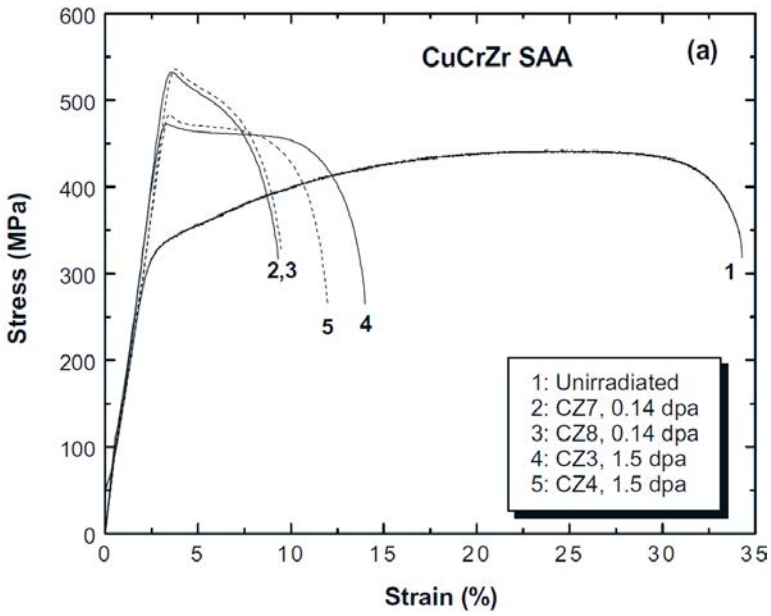


▲ **FIG. 1:** Deep cracking due to thermal fatigue in a divertor target [1]

The particle fluxes experienced by the PFCs lead instead to a plethora of phenomena called Plasma-Wall Interactions (PWI). The PWI requirements put constraints on the choice of materials that can be used as an interface with the plasma, the so-called Plasma-Facing Materials (PFMs). This is the reason why the PFCs are equipped with an armour, made of a PFM, which is the part of the component interacting directly with the plasma. Among the different damages resulting from PWI, the most critical for the lifetime of components is the erosion due to sputtering. Sputtering occurs because, when charged particles collide onto a solid material, they can exchange momentum, through Coulomb collision, with the atoms inside the wall. This process can result in the ejection of atoms from the solid material, which results in an effective erosion of the wall. In PFC, the lifetime due to such process is increased by both increasing the thickness of the armor and choosing an appropriate PFM. Presently, the most promising PFM for fusion reactors is tungsten (W), which being an element with a high atomic number is less prone to sputtering. Another detrimental effect due to PWI is the formation of a nanoscale porous structure, called "fuzz", on the surface of the PFM. Even if the effects of fuzz on the operation of a fusion reactor are yet to be quantified, this phenomenon could potentially lead to an increased possibility ● ● ●



◀ **FIG. 2:** Surface modification on recrystallised W after 10^5 heat pulses (0.8 GWm^{-2}, 0.5 ms long) [2]



▲ FIG. 3: Engineering stress–strain curves of un-irradiated and irradiated CuCrZr [3]. Even at low displacement per atoms (dpa), the material undergoes embrittlement.

● ● ● of arcing, which consists in the formation of short electrical discharges occurring between the plasma and a PFC. Consequently, an increased production of W dust and/or flakes could take place due to erosion.

Neutron irradiation of the materials

The interaction between the neutrons and the atoms inside a solid material is of nuclear nature and leads to irradiation damage. Nuclear reactions with the atomic nuclei can occur. This leads to transmutations, which consists of the generation of other elements that have different properties than the original ones, with subsequent production of light gases such as hydrogen and, most of all, helium inside the lattice material,. This leads to swelling and cluster formation worsening the mechanical properties. In addition to these processes, the lifetime of the components is also limited by the damage generated due to the so-called collision displacements. The elastic scattering, occurring between energetic neutrons impacting onto a solid component, can result in the displacement of the atoms in the walls, effectively rearranging the distribution of the nuclei in the material. Such type of irradiation damage is measured with a quantity called "displacement per atom" (or dpa) and is defined as the number of times an atom is displaced, on average, for a given neutron fluence. Due to irradiation damage, the materials change their thermophysical and mechanical properties, behaving effectively as different materials. Specifically, alloys can, at high dpa, undergo embrittlement. This is a major engineering concern, especially for the structural components which are the parts and systems that support the whole structure of the reactor. Embrittlement is a phenomenon in which a material can no longer deform plastically before ultimate failure, and suddenly fails as soon as a defect is initiated. Naturally, such a behaviour cannot be tolerated in a structural component, whose failure would result in a major damage of the whole plant. At present times, irradiation damage due to collision displacement represents the main limiting factor to the lifetime of the components of a fusion reactor able to deliver electricity to the grid. Figure 3 shows how Copper-Chromium-Zirconium (CuCrZr), which is a fusion-relevant material, loses its ductility already at low dpa [3]. Such a threshold has been up to now more than sufficient for the present fusion devices. However, a reactor generating electric power from nuclear fusion would have a drastic increase in the neutron flux expected on the walls. For this reason, the development of neutron-resistant materials is one of the most active fields in fusion research. For the case of PFCs, which receive the highest neutron load, one of the potential alternatives are Reduced Activation Ferritic/Martensitic steels. However, due to their low thermal conductivity (~10-15 times lower than copper), they can be used only in the PFCs located at the region with heat fluxes in the range of 1 MWm^{-2}. Also, W-based composite materials are investigated, such as W/copper, for the region with highest thermal loads, and W/iron. Indeed, due to its high atomic number, W is less prone to the elastic scattering due to neutron irradiation and consequently only a small amount of dpa is generated in the material. The detrimental effects of dpa accumulation limits ultimately the lifetime of the whole fusion plant, specifically when substantial irradiation damage occurs in the parts of the reactor which cannot be substituted (*e.g.*, vacuum vessel).

The DEMO fusion plant

For DEMO, the European fusion plant currently under design that should supply electricity to the grid in the second half of this century, the expected lifetime of the vacuum vessel is of 6 full-power years (fpy) [4]. Such a value comes from the damage threshold due to the neutron damage of the stainless steel 316L(N), used to manufacture the chamber. During this time, the PFCs will be remotely substituted multiple times. Specifically, the divertor units will be removed after 1.5 fpy due to the neutron embrittlement limit, occurring at ~14 dpa, of the CuCrZr used for the coolant pipes [5]. The first wall, which is the PFC covering most of the plasma-facing surface and the breeding blanket, is instead expected to operate for ~5 fpy before removal [6], since will be made of a RAFM steel, called EUROFER, which shows good mechanical behaviour even at ~80 dpa [7]. Consequently, four divertors and two breeding blankets are expected to be used during the operation of DEMO. Coming up with novel neutron resistant materials, as well as innovative engineering solutions to increase the component lifetime, would therefore impact both the economic and the environmental sustainability of nuclear fusion, since both costs and waste could be substantially reduced. The research is very active on this subject, providing new

potential candidates [8]. Unfortunately, one still lacks the experimental validation of such novel materials since no present neutron source shares both the same energy spectrum and fluence expected in DEMO. A key facility will be IFMIF-DONES, a specific center for material testing under fusion-relevant neutron irradiation, planned to be realised before 2030.

In conclusion, the lifetime of the components of a fusion reactor depends on the different loads experienced by the wall. Several types of damage can arise, depending on the nature of the irradiation. At present times, particular focus is dedicated to investigating synergistic effects of multiple loadings (heat and neutrons, plasma and neutrons, *etc.*). However, the most limiting factor to the lifetime of a fusion reactor is currently the neutron embrittlement due to the accumulation of atom displacements inside the material. In the next decades, crucial data will be provided by IFMIF-DONES, which will play a key role to validate novel neutron resistant materials. ■

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Giacomo Dose is currently a Research Fellow at the University of Rome "Tor Vergata", funded by a EUROfusion Engineering Grant awarded in 2018. He collaborates with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) on the design and development of advanced Plasma-Facing Components for the next generation tokamaks, such as DTT and DEMO.

Acknowledgements

The author thanks Dr. Simone Noce for the useful insight into fusion neutronics, especially regarding the damage threshold of the structural materials, which are planned to be used in DEMO.

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WHERE ARE THOSE PROMISING SOLID-STATE BATTERIES?

Marnix Wagemaker[1], Mark Huijben[2] and Moniek Tromp[3] – DOI: https://doi.org/10.1051/epn/2021504
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In recent years there have been regular reports about a new generation of batteries in which the liquid electrolyte is replaced by a solid material: the solid-state batteries. With a higher energy density and a better safety than current batteries, solid-state batteries potentially would boost electric mobility by enhancing the driving distance of e-cars and prevent extreme battery fires. Why are they not yet implemented in the latest generation of e-cars?

▲ E-cars will profit from solid-state batteries.

The focus of the development of a solid-state lithium-ion battery is to find solid electrolytes that not only have a good lithium conductivity but also show stable behaviour at the interfaces with the electrode materials in the battery. In addition, the resulting battery design must be fit for commercial mass production. Not an easy challenge. After a short introduction on the working principle of the current lithium-ion battery, we review the options. For details we refer to [1].

Lithium-ion battery with liquid electrolyte

Currently, lithium-ion batteries rely on the use of a liquid electrolyte for the transport of lithium ions between the electrodes (figure 1). The positive electrode is made of a material with strongly bound lithium such as for instance $LiCoO_2$; in the negative electrode, made of, *e.g.*, LiC_6 graphite, lithium is loosely bound. A separator prevents direct contact of the electrodes, but allows lithium-ions to pass. The battery cell is flooded by the liquid electrolyte. It is an organic solution

containing lithium salts, which easily penetrates into the pores of the electrodes, thus providing optimal ionic contact. In the charged state, lithium in the negative electrode has a chemical potential energy with respect to the positive electrode. This drives the lithium-ion from the negative electrode material to the positive electrode. Externally, the chemical driving force manifests itself as the battery voltage. Since the electrolyte only allows lithium-ions to pass, the lithium-ions can only migrate from the negative to the positive electrode if the electrodes are electrically connected externally. Once this is the case, the internal chemical energy of the battery is converted into electrical energy during the discharge of the battery.

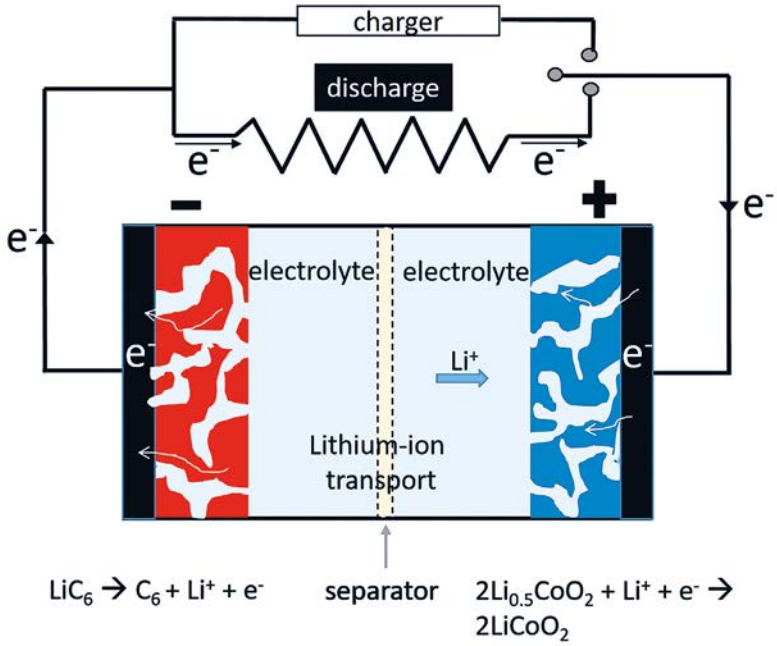
Replacing the liquid electrolyte by a solid electrolyte

Using liquid electrolyte in a battery has a few major drawbacks: Over time, the quality of the contact in the electrodes degrades due to unwanted chemical reactions and consequently the battery performance deteriorates. Additionally, the flammability of the liquid electrolyte and the possibility of leakage present a major safety risk. Replacing the liquid by a solid electrolyte could mitigate both problems. The promise of solid-state batteries is that they would charge quicker, last longer and have a larger energy density. That means that an e-car with a solid-state battery pack could go farther than it would go with an equal-weight conventional lithium-ion battery pack. The application of solid electrolyte materials for energy storage is being studied since more than fifty years. For a long time, the transport of ions such as lithium-ions through the material was not sufficient. However, in the past decade, several breakthroughs have led to solid-state electrolytes with an ionic conductivity that is sometimes even better than that of conventional liquid electrolytes.

Using solid-state electrolyte material would significantly reduce the weight and volume of batteries, because the separator between the electrodes of the battery and a rigid packaging to prevent leakage are both no longer needed. However, no-one has managed to mass produce one at a useful scale yet. It turns out that it is tricky to make them reliable. We go through a couple of options.

Metallic lithium anode

With a solid-state electrolyte it would also become possible to use pure metallic lithium as anode material, or at least, that is the hope. Metallic lithium has an energy density that is ten times higher than that of graphite, which is used in conventional lithium-ion batteries. Other advantages of using metallic lithium are its high electrochemical and thermal stability. However, imperfections at the interfaces between the electrodes and the electrolyte inside the battery can considerably reduce the lifetime and performance of the battery, and can pose safety risks. In addition, the metallic lithium is fragile and reactive, which are features that make mass production of the solid-state batteries challenging.



▲ FIG. 1: Schematic of a rechargeable lithium-ion battery during discharge. The electrolyte separating the two electrodes selectively let pass lithium ions. Electrons are therefore forced into the external circuit.

Solid polymer electrolytes

Solid polymer electrolytes offer the best mechanical flexibility. That is attractive for large-scale production of the batteries and to deal with the volumetric changes of the electrodes during battery cycling. Lithium salts are dissolved in the polymer solution to form positive (cations) and negative (anions) parts in the polymer material. The lithium-ion transport is mediated by the movements of the polymer chains. Higher conductivities of the material is achieved by making the polymer chains more flexible and by fixing the anions such that lithium-ions can move more freely. In this way, the goal is to achieve room-temperature operation of this type of batteries.

Ceramic sulfide electrolytes

Ceramic materials are characterised by a regular crystalline structure with sufficient space for small ions such as lithium to move through them. Lithium-conducting sulfides have an ionic conductivity close to that of conventional liquid electrolyte batteries. Extremely high lithium-conductivity can be achieved by replacing certain elements in the sulfides that make the Li-ion mobility higher. The current record holder is the complex $Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$ with a lithium conductivity of 25 mS · cm^{-1}, which is more than twice the conductivity of liquid electrolytes in current Lithium ion batteries, which is typically 10 mS · cm^{-1}. The mechanical softness of the sulfide-based solid electrolytes which are known as Lithium Super Ionic CONductors or LISICON, allow for good contact at the interface with the electrode. Unfortunately, the electrolytes also have major drawbacks. They are not stable when in contact with the electrodes: the solid electrolyte is oxidised by the positive electrode and/or reduced by the negative electrode, which lowers the conductivity. In addition, they can generate the harmful gas H_2S when they come in contact with water, making large-scale fabrication challenging.

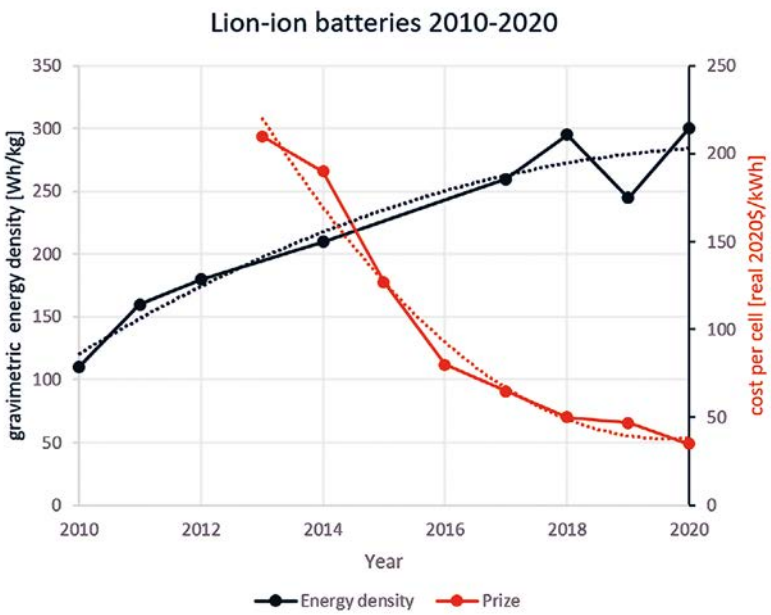
Crystalline oxide electrolytes

In the early 1990s, for the first time oxide materials were used as electrolyte. However, due to the amorphous interlayers of the material , which have no structural arrangement, the batteries had a poor mechanical stability and a low lithium conductivity. In the same period also the first crystalline oxide electrolytes were developed, which had a higher conductivity of lithium-ions because of the regular crystal structure. However, they still had a limited stability when the electrolyte came into contact with a negative electrode of pure metallic lithium. Fortunately, after 2000, it was shown that the crystalline $Li_7La_3Zr_2O_{12}$ was more stable and can work in combination with Li-metal negative electrodes, practically without undesired reactions. By partial replacement by other elements such as Aluminium, Tantalum, Niobium or Gallium, the structure is being further optimised. Currently, among oxide-based electrolytes $Li_{6.65}Ga_{0.05}La_{2.95}Ba_{0.05}Zr_{1.75}Ta_{0.25}O_{12}$ has the best lithium-conductivity of $7 \cdot 10^{-4}$ $S \cdot cm^{-1}$.

Stability of solid-state batteries

The electrochemical stability of a solid-state electrolyte when in contact with the electrodes determines the choice of electrode material and thus the voltage range of the battery. If the electrochemical contact is not stable, the electrolyte will oxidise or reduce, leading to a decomposition at the electrode interface and to unwanted, low-conducting reaction products. Contrary to initial reports of high stability for various solid-state electrolytes, today most materials which are optimal for high energy density unfortunately appear to be unstable in contact with electrodes. Theoretical models of the stability range of promising electrolytes which are in good agreement with the experimental data show that currently there is no solid-state material that has the extremely high lithium-conductivity that meets the desired voltage range for electrode combinations that are necessary to achieve a high energy density. A possible solution is to prevent the electrolyte from decomposing by placing protective thin layers between the electrodes and the electrolyte. The challenge is to develop the structure of such protective layers for controlled and large-scale production.

▼ FIG. 2: Trends in the gravimetric energy density and price of Lithium-ion battery in the period 2010-2020. Data source: BloombergNEF.



Hybrid electrolytes

In addition to single-phase solid electrolytes, hybrid systems such as solid-liquid or polymer-ceramic electrolytes are also being considered. In a composite of a polymer with a ceramic electrolyte, the ceramic would offer high mechanical stiffness and high ionic conductivity while the polymer provides flexibility, simplified fabrication and scale-up and improved electrode adhesion. Again, as in the case of single-phase solid electrolytes, the challenge is to find materials which provide a stable interface between the composite electrolyte and the electrodes in combination with a high Li-ion conductivity.

Modelling

The trial-and-error search for promising new solid electrolyte materials that meet the high standards of ionic conductivity and stability is time consuming and expensive. Therefore, data-driven classification models for ionic conductivity using advanced machine learning algorithms are used to distinguish between potential solid electrolytes with highly conductive and low conductive ionic structures. Density functional theory (DFT) and molecular dynamics (MD) simulations are performed to study the structural properties of the most promising materials, taking into account the basic quantum mechanical interactions of atoms. Also in current working batteries the degradation processes using innovative characterisation techniques is extensively studied. For example, both the ion and the electron dynamics as well as the chemical and structural transformations at the interfaces between electrodes and electrolyte are being studied. With the acquired fundamental understanding, strategies are now being developed to prevent undesirable decomposition at the interfaces between the electrodes and the solid electrolyte with advanced coatings.

Where are the promising solid-state batteries?

Worldwide, researchers are using advanced computational battery models and experimental setups to study the behaviour at the interfaces in solid-state batteries (see, *e.g.*, [1-4]). Many companies such as Toyota, Solid Energy, Infinite Power Solution, Seeo, Sakti3, Front Edge Technology Inc., QuantumScape, Bolloré, BrightVolt, Prologium, SolidPower and Ionic Materials are working at commercialising the new generation of batteries in their products. This, however, turns out to be a great challenge. Of course, most companies do not disclose

which technology they plan to use in their future generation batteries. The QuantumScape company claims to be ahead of the competition in solid-state battery development and has been successful in bringing in investors, including Volkswagen. According to their website, during testing their batteries could be charged to 80% in fifteen minutes and would contain 80% more energy than comparable conventional lithium-ion batteries. However, the question remains whether they will be able to mass-produce their batteries in the short term. The Solid Power company recently received a major investment from Ford and BMW, while Taiwanese Prologium is working closely with a number of Chinese car builders. Toyota has been working on their own technology for many years and owns more than a thousand patents in the field of solid-state batteries. The company announced that it would present the first electric car with solid-state batteries at this year's Olympic Games. That has not happened.

In conclusion, many battery experts worldwide remain skeptical about a large-scale use of solid-state batteries within a short time frame, because it is not easy to mass-produce a battery that is shown to work in the lab. Nevertheless, the potential of solid-state batteries is enormous and well worth keeping a close eye on. ■

Adapted from two articles in Dutch in NTvN 87-7 (2021)

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DEVELOPING THE FUTURE ELECTRICITY GRID

Miro Zeman – Delft University of Technology, The Netherlands – DOI: https://doi.org/10.1051/epn/2021505

We are used to the continuous supply of electricity from a socket. Behind the socket lies a complex system of large power stations, high-voltage cables, transformers and a distribution network. Little has changed in the system over the last fifty years. The ambition to generate sustainable electricity from variable solar and wind energy has an immense impact on the electricity sector and requires major changes in our electricity grid and its operation.

▲ The Electrical Sustainable Power Lab

To facilitate the research needed for the transition of the power grid, Delft University of Technology in the Netherlands, recently has opened the new Electrical Sustainable Power Lab – the ESP lab. In the lab, the Dutch electricity grid is being prepared for the future. It is a lab that provides the ground for realistic tests and large-scale simulations using a digital twin of the real power grid. Using the knowledge and facilities of the ESP Lab, we aim to support and accelerate the energy transition. Let's see what is at stake.

Hybrid networks

Most existing electricity networks are based on alternating current (AC), while the electricity generated from sun and wind provides direct current (DC). To connect the direct current from sun and wind to the AC electricity grid new electronic components – inverters – are being developed. Inverters are very fast switches made of semiconductor materials. Unlike transformers, on which today's AC networks are based, inverters can convert a DC voltage to an AC voltage. To comply with the ambition to generate a large fraction of the electricity demand using

sun and wind energy, the current electricity grids will have to be converted into hybrid AC/DC networks with a significant number of inverters. This is a major challenge.

Variable energy sources

Another challenge is the variability of sun and wind energy sources which, unlike the current fossil or nuclear energy sources, are not fully to our control. Sometimes the wind blows too hard and sometimes not at all. With the sun it is even more complicated: in addition to the day-night cycle, solar radiation can also be disturbed by clouds and there is a strong seasonal dependence in the amount and strength of the solar radiation. The variable nature of these energy sources has consequences for the operation of the electricity system. The operation of the current electricity systems with stable and controllable energy sources is based on the concept that the supply follows the demand. This is relatively easy to do, since the power requirements of consumers are very predictable and you can control the electricity production in the large power stations. In this way, supply and demand can easily be kept in balance.

However, this is not possible with sun and wind as electricity sources, since we cannot influence their availability. The electricity production of a solar plant can quickly switch between a lot of electricity and no electricity at all, depending on the weather. The inertia of the spinning heavy rotor of an electrical generator in traditional power plants is in stark contrast to the rapid response of solar panels to generate electricity. The latter can cause rapid fluctuations in the energy supply that can endanger the stability of the entire electricity grid. The problem can be solved if indeed the use of electricity would follow production or, if this is not possible, if electricity can be stored in, for example, batteries, which can provide the electricity quickly to balance supply and demand on the grid. Once they can be produced cheaply enough, they are expected to become one of the main suppliers of electricity during times when the sun is not shining and the wind is not blowing. Another, quickly emerging option is storage of excess electricity in green hydrogen that can solve seasonal differences in the availability of solar and wind energy.

Stable grids

The electricity grid is a huge system and there is always a chance on a disruption somewhere in the system. There are many possible causes for this, ranging from a broken coffee machine or a cable that is hit by excavation work or a fallen tree. Our current robust electricity grid can cope well with these disruptions thanks to the slowness and controllability of electricity production in the few large power plants. With electricity from renewable sources, supplied by countless wind turbines, photovoltaic systems and inverters, the disturbances are not easily absorbed and can have very devastating consequences for the electricity grid. Consequently, maintaining the stability of the future electricity supply requires the design and development of new rapid protection schemes.

New electricity producers

The rise of renewables has added many new energy producers, because each wind turbine or solar panel is a power plant in its own right. Suddenly, citizens with their own solar panels are prosumers, producers and consumers at the same time. As a supplier, they are highly variable, as wind speeds and solar radiation fluctuate. As a result, the current in the power grid can flow in two directions and change its direction quickly. The big change for the whole system is that the distribution part of the electricity supply, which until now was passive - consumption of electricity - becomes an active part of the system - consumption and production of electricity.

Electrification of society

We also see a further electrification of society. Transport is becoming electric, as is heating, and industrial processes are largely driven by electricity. This not only means more and more electrical devices in the system, but also an increasing demand for sustainable electricity. In addition to electrification, digitalisation is a growing trend in society. The digitalisation of the electricity supply leads to more sensors in the system which deliver information about the status of the power supply and the condition of the components. Many new components, such as inverters, digital transformers and batteries, have built-in electronics, making them intelligent and enabling them to communicate with each other. The data are collected and processed by grid operators enabling them to take operational decisions. It leads to a smart grid system that provides better and automated control of the system. Connecting and integrating a broad variety of new components such as inverters and electric cars, and energy sources such as solar panels and wind farms to the grid, and merging and transporting electricity has become a complex challenge.

Reliable power supply

The most important condition that the transition of the power supply must meet is to maintain the high reliability of the current systems. The transition is often compared to renovating a store while the sale goes on. Less CO_2 emission and more sustainability in the electricity •••

“The inertia of the spinning rotor of an electrical generator is in stark contrast to the rapid response of solar panels to generate electricity.”

sector requires radical actions, but we also have to ensure that everyone continues to receive electricity, heat and gas properly.

The need for research facilities

The growing share of renewable energy sources and power electronics components requires a new design and control of electricity grids. It also requires the introduction of new economic and financial models to give all stakeholders, including the prosumers, access to the energy market. Worldwide, universities are studying the different aspects of the energy transition to develop solutions to the challenges. Some are developing methodologies for planning, designing and operating smart medium and low-voltage networks with large-scale electricity generation from renewable energy sources and storage to increase flexibility of supply. Others focus on the theory of energy conversion and technologies for electromechanical energy conversion and power electronics. Modelling and simulations provide insights into topics such as supply and demand management, microgrids, integration of energy storage, markets and pricing mechanisms, and safety and security.

Today, most new consumer equipment, such as electric cars, batteries, mobile phones, computers or LED lamps, operate on DC power. But, as mentioned above, our electricity grid runs on alternating current, so inverters are needed to first convert DC electricity to AC and then vice versa. To prevent conversion losses, autonomous electricity networks, so-called microgrids, that only work with DC electricity are designed and tested. Inverters for the (contactless) charging of electric cars and bicycles are being designed. Scientists study the role of car batteries and neighbourhood batteries as a stabiliser of microgrids and also of the entire electricity system with large-scale power plants that increase the flexibility of electricity supply. The main challenge is the integration of new technologies and components for electricity generation and storage, digital technologies for information and communication and models for markets and control in the existing electricity system. And the integration must be done without compromising system performance. Stability, protection and cyber-physical security issues of the future system are studied and control rooms of the future are being developed that can control the ever-faster dynamics in the entire electricity grid and prevent instability in the grid.

The ESP Lab

To facilitate the research for the energy transition and to physically bring together the relevant research, TU Delft has opened on 1 October 2021, a new dedicated laboratory, the Electrical Sustainable Power Lab (ESP Lab). In the ESP Lab, crucial elements from the electricity grid, such as high-voltage facilities, wind and solar energy, energy storage and distribution networks, are combined into one functioning whole. The laboratory has advanced research and testing facilities to design and fabricate new materials, components, technologies and systems for the future sustainable energy system, and to characterise, optimise and validate them. Examples include solar cells, electronic power converters, electrical machines, microgrids, smart grids, high voltage AC and DC components, monitoring and diagnostics of components and power grids. The ESP Lab is ideally suited for the development of individual components and technologies needed for the future energy system.

To provide usable and proven solutions for a safe and reliable energy supply in the future, one must not only test the individual parameters of these new technologies and components, but, more importantly, one must test their performance at the system level. The ESP Lab offers scientists and researchers exactly this unique opportunity. It provides the facilities and a platform for Energy Transition Solutions to collaborate on integrated system solutions for various areas of electricity processing, such as electricity generation, transmission, distribution and use. Supercomputers that can simulate the behaviour of large power grids play an important role within the ESP Lab. What is special is that you can connect real devices in the lab to those powerful computers. For example, if you want to connect an offshore wind farm or a large neighbourhood battery to a power grid and you want to know what the consequences are for the stability of the grid. Or how you should intervene to keep the grid working properly. These questions can be answered using a digital twin, a digital copy of the electricity grid under investigation. On a digital copy, these kinds of experiments and investigations are carried out without running the risk of breaking anything in the real power grid. Smart equipment will play an increasingly important role for a sustainable and safe electricity grid. The smart electronics can make the grid more efficient and reliable if this equipment is controlled by good control systems. These control systems are being developed and tested by researchers in the ESP Lab using supercomputers.

With the results of the research, the ESP Lab can advise grid operators, who can then better deal with changes aimed at the electricity grid of the future. ■

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Hitting New Milestones and Accelerating the Commercialisation of Quantum Computing in Europe

Just over a year ago Rigetti Computing, a California-based developer of quantum computers was granted £10 Million by Innovate UK, the UK government's research innovation agency, to accelerate the commercialisation of quantum computing in the UK.

Matt Martin, Director of Engineering at Oxford Instruments NanoScience, talks to Mandy Birch, SVP of Technology Partnerships at Rigetti, about the progress that has been made on the project in the last year. Birch also covers the importance of collaboration on a project of this scale, and the future goals for this project.

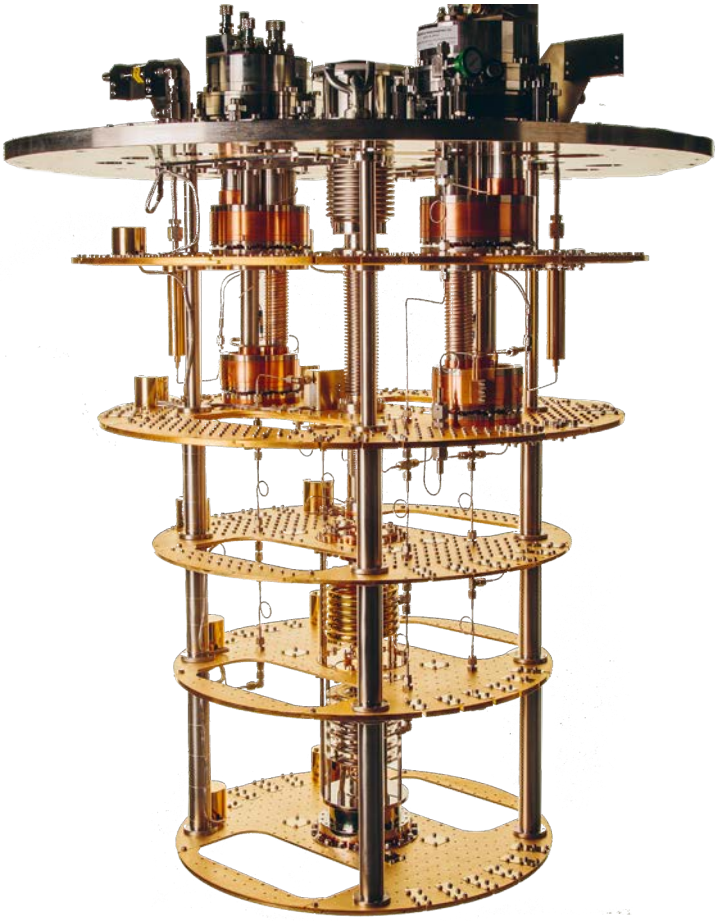
Can you provide an update on the Innovate UK project and what's been achieved in the past 12 months?
It's been a busy year but through the collaboration between the various partners involved, we have managed to reach a significant milestone in the development of our quantum system - the complete setup of a Rigetti quantum computer in the UK moving on to testing, characterisation and selection of the Quantum Processing Unit (QPU). This milestone has only been possible thanks to the contributions of the team and the close collaboration with Oxford Instruments in particular who provided the ProteoxLX cooling system and the set-up of the computing facility infrastructure in Oxford.

Who are the various partners that you're working with as part of the project?
In addition to Oxford Instruments, we are also working with the University of Edinburgh as well as Phasecraft and Standard Chartered through cloud-based quantum computing access to assist with development activities. While developing our system, the University of Edinburgh has supported foundational quantum machine learning (QML), while our partners at Phasecraft have been able to use quantum-mechanical simulations to develop higher-performance batteries. Meanwhile, our partnership with Standard Chartered allowed us to explore volatility predictions within the financial markets. It's exciting to consider just how many applications quantum computers can have.

What can we expect to see from this project in the future?
We are currently targeting commercial availability in early 2022. But the work is far from over. We made sure to design our computer with future-proofing in mind. Using OI's ProteoxLX system with its fully customisable, modular and removable secondary insert, this allows the qubit integration to be easily scalable to larger numbers of qubits and more advanced architectures, allows the resulting quantum computer to remain up to date as new processors become available.

Our goal for the future is to have the ability to solve real-world problems with the quantum computer within the next five years. In order to achieve this, we will focus on scaling the current application prototypes to larger qubit counts while mitigating computational errors, with the goal of upgrading the system and deploying a larger, higher quality QPU in the second half of 2022. ■

FOR MORE INFORMATION: https://nanoscience.oxinst.com/blog/accelerating-uk-quantum-computing-with-rigetti.



DIGITAL GRIDS BEYOND SMART GRIDS
CHALLENGES TO MAKE FUTURE ELECTRIC GRIDS STABLE AND RESILIENT

Jose Luis Domínguez-García – DOI: https://doi.org/10.1051/epn/2021506
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Novel technologies are changing our understanding of the electrical grid. These novel concepts, including power electronics, energy storage, ICT and renewable energy make the electrical grid highly controllable but at the same time also vulnerable. The future grid will introduce novel dynamics, stability challenges and security issues to be handled.

Current energy systems were designed more than 100 years ago and have been only incrementally modified since. They worked well in the time of vertically integrated, centrally supplied generation models, but this was when efficiency and resilience were less important. In addition, the EU is targeting to reduce the emission of greenhouse gasses to net zero by 2050 according to COP25[1] in Madrid. The potential contribution of the power sector to realising these goals through the integration of renewable energy sources (RES) is highly significant. Indeed, the high reliance on RES and the electrification of energy sectors as a key factor in tackling undesired climate change was underscored in COP24 Katowice [1]. In fact, some future European energy scenarios even foresee a RES penetration close to 100% by 2050 [2]. In order to achieve this ambitious RES penetration target, RES and other elements will have to strongly support all aspects of power system stability as well as security of the electricity supply.

Energy Grid disruption

The electricity sector is changing its paradigm making it necessary to adapt the industrial sector to such a new model. The change is led by the irruption of the renewable

[1] https://home.kpmg/xx/en/home/insights/2019/12/key-outcomes-of-cop25.html

energies, energy storage, the integration of technologies of information and communication and internet, which has provoked the evolution of the classic distribution grid to the Smart Grid, and now beyond that to the Digital Grid.

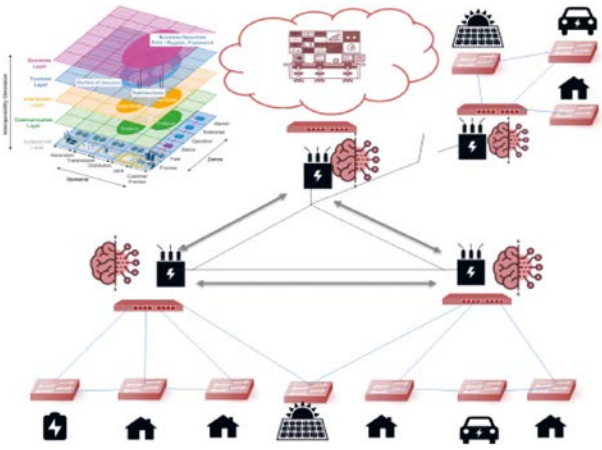
The digital grid is the digitisation of electricity networks using advanced technology. It allows two-way communication between the utility and the network, including its customers, and enables insight, automation and control across the utilities' operations, empowering utilities to improve reliability, availability and efficiency of the grid. The Digital Grid is the concept aiming to connect decentralised power from renewables, microgrids and virtual power plants, as well as energy storage alongside traditional bulk generation; to harness the potential of connected homes and devices and the internet of things as well as improve the reliability of current grids by making them smarter, able to self-detect and self-heal outages, and to re-route power as needed.

The Digital Grid concept is a key part of the future electrical grid and increases system complexity since it interrelates the electrical system with the communication network. The evolution of the future electrical grid on the distribution network especially in urban areas may include enhanced communication capabilities. The penetration of renewable energies and energy storage leads to the application of mini and micro-grids such as those for small communities, large buildings or manufacturing facilities.

Electrical Grid modelling: new dynamic behaviour

Classical electrical grid dynamics are governed by large synchronous generators with large inertia. These electrical systems have been commonly modelled and represented, in a high-level way, as a group of interacting oscillators which could be modelled for example as a Kuramoto-like model [3]. However, the future electrical grid with the introduction of novel highly non-linear elements and inertia reduction, is changing such behaviour and the stability concepts and definitions [4]. Different time-frames and frequencies will be interacting. In the • • •

▾ **FIG. 1:** High-level representation of a Future Electrical Grid, including distributed management; a highly flexible and meshed grid.



▸ FIG. 2: High-level representation of clusterisation and self-healing concept grid based on a grid form by microgrids [5]. Each microgrid, compound by renewable sources, energy storage and loads, is isolated to operate autonomously. In this way, the electrical grid will become a grid of grids.

same way, different physical worlds like Alternate Current (AC) and Direct Current (DC) will be connected and decoupled at the same time by the power converters. Power converters are switching-based elements with high frequency responses and non-linearities increasing system stability complexity. Additionally, the Digital Grid has a direct interaction with the communication network which also poses restrictions and adds complexity due to its discrete nature within a continuous operation world. To understand and control such novel dynamic behaviour and the related risks and limitations including stability, synchronisation etc, is of great relevance.

Electrical system resilience

The electrical grid is considered one of the central critical infrastructures which needs to be protected. In this regard, a key aspect is ensuring its resilience taking advantage of the novel capabilities that the new technologies integrated on the grid may bring. One of the key elements leading to increased resilience and security is the novel grid automation system and monitoring devices which provide high visibility of grid status as well as give the opportunity to modify it. In this regard, microgrids and nano-grids may play a key role. These grids are intended to be more or less self-sufficient in terms of power generation and may be key elements for increased resilience. In addition, the application of Internet-of-Things-based elements – both as devices and protocols - allows the acquisition of increased amounts of data and data sharing among components.

In this line, different key developments are required aiming to deal with the resilience-cycle phases such as planning, detection, actuation/mitigation and recovery. For improving planning, there is the need to take advantage of previous information and knowledge, in order to anticipate and prepare the grid for such disruptions; in this sense, risk assessments tools [5] are required in order to identify and predict the vulnerable zones of the electrical network. Then, when an event occurs, there is the need to detect what happened. In the electrical grid, some events may result in similar disruptions from the electrical perspective, but the potential response and correction will be different. Thus, fault identification and location techniques [6] may help to determine what happened; speeding up the process of potential correction. To do this, the novel sensors and Artificial Intelligence will be of relevance. Then, we need to actuate to mitigate the impact of the disruption by responding and adapting the electrical grid. This can be achieved by isolating the impacted elements and reconfiguring the lines for ensuring the power flow (self-healing) or in case of special type of grids, take advantage of microgrid concepts and split the grid in small, stable, secure pieces (clusterisation) [7]. Finally, there is the need to recover the grid to its previous normal operational stage, which require coordination and synchronisation of the grid elements in order to ensure secure and stable reconnection.

What else can we expect?

The electrical grid is experiencing a rapid evolution. It has been a quite classical system for many years, and in the last 15 it has been transformed. It is expected to continue like this in the coming years by absorbing and integrating novel technologies. Leading us to the final question: What else we can expect? ■

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NOBEL PRIZE 50 YEARS AGO

As we recall the major contributions of Professor Dennis Gabor that resulted in his Nobel Prize in Physics in 1971 for the invention of holography, it is interesting to put his impact on science, technology, as well as humanity, in a broader context so as to better understand his experiences, and recognize the very significant role that he played in his time.

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▲ Dennis Gabor receiving his 1971 Nobel Prize for Physics from King Gustav Adolf of Sweden.

Born as Günszberg Dénes in Budapest, Hungary, in 1900 into a well-to-do family that had converted to Lutheranism but was nevertheless affected by the air of the times, and decided to change the family surname to the more Hungarian sounding "Gábor" in 1902.

As an adolescent, while receiving an excellent Gymnasium education in his home town, he and his older brother enjoyed a home laboratory to run relatively advanced physics experiments for the time with X-rays or radioactivity.He was also fascinated by the calculus, voraciously reading relatively advanced textbooks. The two drawings that are included in this brief article, show that Dénes was also artistically imaginative and talented.

During the last year of the First World War, Dénes served with the Hungarian artillery against Italy, and after the armistice in 1918 he started his engineering studies at the Technical University of Budapest. He then moved to the Charlottenburg Technical University in Berlin with his parents' support, and graduated with an Engineering degree in 1924.

He pursued his studies in Berlin to obtain a doctorate in engineering in 1927 under Professor Ernst Orlich, working on electron optics to design and experiment cathode-beam oscillographs for the analysis of high-voltage electric transmission lines. His PhD thesis focused on the "Recording of Transients in Electric Circuits with the Cathode Ray Oscillograph", and this early work would lead him later to other devices such as electron microscopes and TV tubes. During his years as an engineering PhD student in Berlin, he also pursued his interest in physics by taking advantage of lectures and research groups surrounding the likes of Einstein, von Laue, Max Planck *etc.*

After his PhD, he joined the Siemens & Halske AG company as a research engineer, staying there until 1933. At Siemens he made some inventions such as the high-pressure quartz mercury lamp with superheated vapour with a molybdenum heat-resistant seal, that has been widely used in street lamps. Throughout his career, from 1928 until 1971, he filed no less than 62 patents, and he has often stated that he considered himself more of an inventor and engineer than a physicist.

In 1933-1934 he left Berlin because his contract at Siemens & Halske was not renewed, and briefly moved back to Budapest because of the threats posed for him personally by the rise of the Nazis in Germany. Then he was fortunate enough to be able to join the British Thomson-Houston (BTH) Co., in Rugby (England), on an inventor's contract, since regular employment as a foreigner was very difficult to obtain at the time in the UK (and elsewhere in Europe).

At BTH he initially worked on gas-discharge tubes, and later moved to the BTH Research Department as a regular employee. In Rugby he met his future wife, Marjorie Louise Butler, whom he married in 1936 and with whom he lived till his death in London in 1979. In 1946 he acquired British citizenship and was still at BTH when he invented holography in 1947, experimenting with light from a heavily filtered mercury arc. However, it was the invention of the laser in 1960 that provided the coherent source of light that allowed the creation of the first holograms in 1964, finally making holography commercially available.

Indeed, Dennis Gabor developed the early principles of holographic theory while trying to make improvements to the resolution of the electron microscope by exploiting the phase of the electron beams. However, progress in the field was very slow, and the value of these ideas only became broadly apparent when efficient sources of light, namely the laser, became available. Indeed, to form a simple hologram, or "wave-front reconstruction" as it was initially called, one can exploit the image formed on a sensitive film plate or paper by the interference patterns of two light waves that have different phases.

▲ **FIG. 1:** Drawing by Gabor when he was around 10 years old. Provided by courtesy of the Library of the Hungarian Academy of Sciences.

This apparently simple idea has given rise to many applications both in science and for commercial use, such as barcode readers, credit card security, the capture of three dimensional images, for measurements related to particles in physics, *etc.*

In 1949, Dennis Gabor (as he had become known in the UK) finally transferred to academia by accepting an appointment as Reader in Electronics at the Imperial College of Science and Technology in London, in the Department of Electrical and Electronic Engineering. He was then promoted to Professor of Applied Electron Physics only after he was elected a Fellow of the Royal Society in 1956. During his time at Imperial he was also associated for some years, from 1950 to 1953, with the AEI Research Laboratory in Aldermaston, where he worked on holography.

In several respects, he was similar to his predecessor, the great astronomer, physicist, mathematician and philosopher Ḥasan Ibn al Haytham (Latinized as Alhazem, c. 965 – c.1040) of the Islamic Golden Age, who is viewed as the father of modern optics through his "Book of Optics" (Kitab al-Manazir or "Book ● ● ●

As elegantly stated by the distinguished French physicist Edouard Brézin (private communication) and former President of the French Academy of Sciences:
"If Dennis Gabor was awarded the 1971 Nobel prize in physics 'for his invention and development of the holographic method', his contributions to science and electrical engineering span more than half a century. Before the actual implementation of his ideas, he realized early in his career ... that for ideal imaging, one should use not simply the amplitude of the wave, but also its phase. Initially he (Gabor) had in mind holography as a tool for electron microscopy, but after the invention of lasers, it became available and familiar to all with visible light. He had kept all along his life an interest for new technological developments in the fields of electronic optics, information processing and storage. His career is a model of cross-fertilization between very fundamental ideas and major technological developments."

▲ FIG. 2: Drawing by Gabor when he was around 10 years old. Provided by courtesy of the Library of the Hungarian Academy of Sciences.

● ● ● of Views or Landscapes") that survived through its Latin translation.

Indeed, with his curiosity about the role of phase in light, but also in the role of phase in sound signals and speech (*e.g.*, over telephone lines or wireless communications), Dennis Gabor is a precursor of the theory and applications of the mathematics of wavelets. The "Gabor Wavelet" tries to capture the time, phase and frequency nature of signals, as well as the orientation of such signals if we consider small but important spatial features in images. These ideas are now widely used, even for the recent detection of gravitational waves.

Thus Gabor's wavelet representation, first expounded in a paper published in 1946, includes a spatial template modulated by sinusoidal waves of fixed frequency ω_0 that propagate along different directions θ with different phases φ. Anchored in physics through the Uncertainty Principle, these ideas provide a powerful and useful generalization of Fourier series that has endured, and also resulted in the theory of wavelets which has been thoroughly developed by leading contemporary scientists such as the Abel Prize-winning mathematician Yves Meyer who expressed (personal communication) his admiration for Dennis Gabor, both as an individual who stayed on in Europe during the war years, despite his opportunity to emigrate to the USA, and for his precursory work on the time-frequency representation of signals motivated by the theory of communications.

Both Ibn al-Haytham and Gabor were also concerned with societal and philosophic issues, and each of these two "scientists of optics" expressed their interest in manners appropriate for their time: theology for Ibn al-Haytham, and the need to design the future with the help of science and engineering in the case of Dennis Gabor. Thus, Dennis Gabor's persona would be incomplete to the reader if we did not mention his engagement and efforts for the creation of the Club of Rome, which was one of the very first institutions to address the sustainability of our planet, based on ideas expressed by the Turkish-American system scientist Hasan Özbekhan (1921-2007), Professor at the Wharton School of the University of Pennsylvania, in works such as "The Predicament of Mankind" (Report to the Club of Rome), and "Toward a General Theory of Planning" (1968), regarding the need to investigate multiple options and paths into the future, going beyond the "natural" and empirical selection of the "one" pathway into the future that is dictated by events that we do not control.

In addition to Fellowship of the Royal Society (1956), Dennis Gabor was elected Honorary Member of the Hungarian Academy of Sciences (1964). Though he was not awarded a Knighthood, which would have been usual for a British Nobel Prize Winner, he was awarded the UK honour of Commander of the British Empire (CBE) in 1971, as well as several honorary doctorates and prizes including the Institute of Electrical and Electronic Engineers' (New York) Medal of Honor, and the Albert A. Michelson Medal of the Franklin Institute in Philadelphia. ■

Dennis Gabor has the good fortune to be much loved and admired in his home country Hungary, and widely recognized internationally. The NOVOFER Foundation of Budapest has been awarding for more than thirty years annual "Gabor Prizes" to Hungarian born scientists and innovators. The author's Hungarian colleagues, such as Professor Lajos Hanzo of the University of Southampton (private communication), have shared the inspiration they received from Dennis Gabor's example when they were high school and university students. A High School in Budapest is named after him. The International Society of Optical Engineering (SPIE) gives the annual Dennis Gabor Award, and the Royal Society of London awards the Dennis Gabor Medal to commemorate the contributions of this exceptional engineer scientist. Berlin also remembers him with the Dennis Gabor Strasse in Potsdam.

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New EPS Historic Sites

In 2021, seven EPS Historic sites have been inaugurated:
7 April 2021 – Sonnenborgh Museum and Observatory in Utrecht, Netherlands
7 June 2021 – City of Jena, Germany
6 August 2021 – The buildings where Anders Jonas Ångström worked in Uppsala, Sweden
6 October 2021 – Museé Ampère, Lyon, France
12 October 2021 – Cyclotron Hall in Louvain-la-Neuve, Belgium
15 October 2021 – Magnus-Haus, Berlin, Germany
19 November 2021 – Zeemanlaboratorium, Amsterdam, The Netherlands
(will be postponed due to COVID-19 measures)

Sonnenborgh Museum and Observatory in Utrecht, Netherlands.

This is where meteorologist Christophorus Buys Ballot formulated his famous law and where the Royal Netherlands Meteorological Institute (KNMI) was founded in 1854. In the 20th century the Dutch astronomers Marcel Minnaert and Kees de Jager made Sonneborgh a place of scientific importance. In 1961 De Jager founded the Laboratory for Space Research at Sonnenborgh. Originally part of the fortifications of the city, today Sonnenborgh is a well- preserved historic city observatory as well as a popular museum.

The city of Jena, Germany

Jena has had an extraordinarily high density of historic buildings that are of vital importance for physics and astronomy. That is why the entire city has been declared EPS historic site. The series of historic sites begins with the university's founding site and continues all the way through the Jena observatory in the "Schillergasse". The focus is, of course, on optics with, among others, the "Hellfeldsches" House in the "Neugasse", where Ernst Abbe founded his microscope theory, as well as buildings of Jena physics on "Helmholtzweg" and "Fröbelstieg". Furthermore, solid state physics has a long tradition in Jena as well as theoretical physics, for example with its contributions to gravitaional physics.

Ångström's lab in Uppsala

The EPS Historic Site in Uppsala is marked by a plaque on a stone fundament just outside the building that hosted the laboratory of Anders Jonas. Ångström studied a wide range of physical phenomena such as the variations of the terrestrial magnetic field, the comets, the theories of elasticity and heat conductivity and, most importantly, he was a pioneer in the field of experimental optical spectroscopy. Ångström performed meticulous measurements of the Sun and produced the first solar atlas with wavelengths in the metric system, which also led to the introduction of the unit of 1 Ångström = 10^{-10} m, widely used in modern spectroscopy and crystallography.

EPS awards and distinctions during the year 2021

The EPS congratulates the 2021 laureates for EPS prizes and distinctions for their outstanding achievements in physics across Europe and around the world. The EPS is grateful to the physics community for submitting the truly excellent nominations received. The EPS highly appreciates the work by the EPS Divisions and Groups in identifying individuals and their research that contribute to the development of physics and our understanding of our world.

EPS-DPP PhD Research Awards

The 2021 EPS-DPP PhD Research Awards have been attributed to **Audrey Chatain** (Université Paris-Saclay, France) for her thesis on 'Aerosols-plasma interaction in Titan's ionosphere', to **Alexandra Dudkovskaia** (University of York, United Kingdom) for her thesis on 'Modelling neoclassical tearing modes in tokamak plasmas', to **Mario Galletti** (University of Lisbon, Portugal) for his thesis on 'High contrast front-end for a petawatt laser system designed for electron acceleration & High intensity laser-matter applications towards advanced compact particle accelerators', and to **Andrea Pavone** (Technical University of Berlin) for his thesis on *'Machine learning approximation of bayesian inference in nuclear fusion'.*

EPS Emmy Noether Distinction

The Summer 2021 EPS Emmy Noether Distinction was awarded to **Sara Bolognesi**, CEA – IRFU, France, *'for her development of data analysis techniques that conclusively improved the sensitivity of the CERN-CMS experiment, thus allowing the discovery of the Higgs boson and the first measurement of its spin and parity'.*

EPS High Energy and Particle Physics prize

The 2021 EPS High Energy and Particle Physics prize was awarded to **Torbjörn Sjöstrand** and **Bryan Webber**, *'for the conception, development and realisation of parton shower Monte Carlo simulations, yielding an accurate description of particle collisions in terms of quantum chromodynamics and electroweak interactions, and thereby enabling the experimental validation of the Standard Model, particle discoveries and searches for new physics'.*

EPS Liquid Matter Prize

The 2021 EPS Liquid Matter Prize was awarded to Professor **Daan Frenkel** *'for his pioneering work in using computer simulations to map out the remarkably rich liquid crystal phase behaviour of hard rod-like and plate-like particles, which has inspired generations of young researchers'.*

EPS/QEOD Prizes

The 2020 EPS-QEOD Prize for Research in Laser Science and Applications was attributed to **Sergey Bozhevolnyi**, Center for Nano Optics, University of Southern Denmark, Odense, *'for seminal contributions to surface-plasmon polaritons and the developments of plasmonic metasurfaces'*.
The EPS/QEOD Thesis Prizes (fundamental aspects) were awarded to Dr. **Yu Renwen**, Stanford University, CA, USA, PhD thesis at ICFO – The Institute of Photonic Sciences, Barcelona, Spain. Title: Toward Next-Generation Nanophotonic Devices, and to Dr. **Gonçalves Paulo André Dias**, ICFO – The Institute of Photonic Sciences, Barcelona, Spain, PhD thesis at Technical University of Denmark. Title: Plasmonics and Light–Matter Interactions in Two-Dimensional Materials and in Metal Nanostructures: Classical and Quantum Considerations.
The EPS/QEOD Thesis Prizes (applied aspects) were awarded to Dr. **Karpov Maxim**, Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland; PhD Thesis at École Polytechnique Fédérale de Lausanne. Title: Dynamics and applications of dissipative Kerr solitons, and to Dr. **Pedreros Bustos Felipe Ignacio**, LAM - Laboratoire d'Astrophysique de Marseille, France; PhD Thesis at Johannes Gutenberg Universität-Mainz, Germany. Title: Mesospheric magnetometry and optimization of laser guide stars.

EPS-SNPD Early Career prize

The EPS-SNPD Early Career prize 2021 was awarded to **Federico Battiston**, Central European University, Vienna, *'for his outstanding work on nonlinear dynamics and emergent collective phenomena in multilayer and higher-order networks, including diffusion, synchronization, social and evolutionary processes'*, and to **Caterina De Bacco**, Max Planck Institute for Intelligent Systems, Tuebingen, *'for her outstanding work on statistical physics of random walkers on random graphs, stochastic search processes, routing optimization on networks and effective algorithms for community detection'.*

EPS Statistical and Nonlinear Physics Prize

The EPS Statistical and Nonlinear Physics Prize 2021 was awarded to **Albert-László Barabási**, Northeastern University and Harvard Medical School, Boston & Central European University, Budapest, *'for his pioneering contributions to the development of complex network science, in particular for his seminal work on scale-free networks, the preferential attachment model, error and attack tolerance in complex networks, controllability of complex networks, the physics of social ties, communities, and human mobility patterns, genetic, metabolic, and biochemical networks, as well as applications in network biology and network medicine'*, and to **Angelo Vulpiani**, Sapienza University, Rome, *'for his seminal contributions to statistical and nonlinear physics, touching fundamentally important issues in dynamical systems theory and statistical mechanics, including the mechanism of stochastic resonance, multifractality of invariant sets of dynamical systems, the dynamics and multifractal properties of turbulent flows, chaos in Hamiltonian systems, and the limits of predictability in complex systems'.*

Fresnel Prize

The Fresnel Prize (fundamental aspects) was awarded to Prof. **Zuerch Michael**, University of California Berkeley, USA *'for outstanding contributions to the field of ultrafast condensed-matter science and the application of linear and nonlinear X-ray spectroscopies for investigating of quantum phenomena'.*

The Fresnel Prize (applied aspects) was awarded to Dr. **Margherita Maiuri**, Politecnico di Milano, Italy, *'for outstanding achievements in ultrafast optical spectroscopy, unveiling primary light-induced processes in bio-molecules and nanostructures with sub-10-fs pulses'.*

Giuseppe and Vanna Cocconi Prize

The 2021 Giuseppe and Vanna Cocconi Prize was awarded to the **Borexino Collaboration** *'for their ground-breaking observation of solar neutrinos from the pp and CNO chains that provided unique and comprehensive tests of the Sun as a nuclear fusion engine'.*

Gribov Medal

The 2021 Gribov Medal was awarded to **Bernhard Mistlberger** *'for his groundbreaking contributions to multi-loop computations in QCD and to high-precision predictions of Higgs and vector boson production at hadron colliders'.*

IBA-Europhysics Prize

The 2020 IBA-Europhysics Prize was awarded to Professor **Thomas Haberer**, Heidelberg University Hospital, Germany, *'for outstanding scientific discoveries and innovative technological breakthroughs in the use of high energy accelerators and heavy ion beams for the Heavy Ion Cancer therapy'*.

Outreach Prize of the HEPPD

The 2021 Outreach Prize of the High Energy and Particle Physics Division of the EPS is awarded to **Uta Bilow** and **Kenneth Cecire** *'for the long-term coordination and major expansion of the International Particle Physics Master Classes to include a range of modern methods and exercises, and connecting scientists from all the major LHC and Fermilab experiments to school pupils across the world'*; and to **Sascha Mehlhase** *'for the design and creation of the ATLAS detector and other interlocking-brick models, creating an international outreach program that reaches to an unusually young audience'.*

Young Experimental Physicist Prize

The 2021 Young Experimental Physicist Prize of the High Energy and Particle Physics Division of the EPS is awarded to **Nathan Jurik** *'for his outstanding contributions to the LHCb experiment, including the discovery of pentaquarks, and the measurements of CP violation and mixing in the B and D meson systems'*; and to **Ben Nachman** *'for exceptional contributions to the study of QCD jets as a probe of QCD dynamics and as a tool for new physics searches, his innovative application of machine learning for characterising jets, and the development of novel strategies on jet reconstruction and calibration at the ATLAS experiment'.*

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