



Select Committee on Science and Technology

Corrected oral evidence: The role of batteries and fuel cells in achieving net zero

Tuesday 16 March 2021

10 am

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Members present: Lord Patel (The Chair); Baroness Blackwood of North Oxford; Baroness Brown of Cambridge; Viscount Hanworth; Lord Kakkar; Lord Krebs; Baroness Manningham-Buller; Lord Mitchell; Baroness Rock; Lord Sarfraz; Baroness Walmsley; Baroness Warwick of Undercliffe; Lord Winston.

Evidence Session No. 2

Virtual Proceeding

Questions 20 - 31

Witnesses

Professor Serena Corr, Chair in Functional Nanomaterials, and Director of Research, Department of Chemical and Biological Engineering, University of Sheffield; Professor Paul Shearing, Professor in Chemical Engineering, University College London; Dr Jerry Barker, Founder and Chief Technology Officer, Faradion Ltd; Dr Melanie Loveridge, Associate Professor, Warwick Manufacturing Group, University of Warwick.

USE OF THE TRANSCRIPT

This is a corrected transcript of evidence taken in public and webcast on www.parliamentlive.tv.

Examination of Witnesses

Professor Serena Corr, Professor Paul Shearing, Dr Jerry Barker and Dr Melanie Loveridge.

Q20 **The Chair:** Good morning, particularly to our witnesses. Thank you very much for joining us this morning. We value your time very much, and what you have to say even more so.

I shall start with batteries. I have a three-part question. What is the current development in batteries in the past five years or so? What are the current limitations on the batteries that are available? What breakthroughs might be needed for the future capacity of the batteries and whatever other issues there might be?

Professor Serena Corr: Good morning. I am professor in chemical and biological engineering and in materials science and engineering at the University of Sheffield. My research interests are in the development and characterisation of energy storage materials. I lead one of the multi-institutional major investments in cathode development by the Faraday Institution called FutureCat.

To answer your question, it is fair to state that lithium-ion batteries have revolutionised the portable electronics industry. We are now seeing batteries not only continuing to power our mobile phones and laptops but increasingly penetrating the transportation market. We need to carefully consider how the Covid pandemic may have influenced car sales. The year 2020 saw a marked increase in the sale of battery electric vehicles, which now account for 6.6% of the overall 2020 market share. That is an increase of 5% in just one year, and it was a challenging year, so I think we will start to see batteries contributing to UK decarbonisation efforts. That will only increase, both with the uptake of battery electric vehicles and with the development of the charging point infrastructure that will support that uptake, as well as contributions of batteries to utility-scale storage and how that integrates with and reduces renewable curtailment. So there is lots of possible growth.

Advances in battery innovation are driven by interfaces. That idea works really well on a number of levels. Performance within the battery itself is governed by behaviours and interfaces, but technological advances are driven by collaborative research at the interface of specialities, such as chemistry, materials, engineering and social sciences. In the UK, we have been particularly good at this, with the establishment of the Faraday battery challenge. We have a long-term commitment now to fundamental and translational research that brings together a community of researchers to tackle a defined set of challenges that invigorates research across academia and industry collaborations.

Professor Paul Shearing: I am professor of chemical engineering at UCL and I hold the Royal Academy of Engineering chair in emerging battery technologies. I lead two projects for the Faraday Institution, one on lithium-sulfur technology called LiSTAR and one on battery safety called SAFE-BATT. Thank you for the invitation to speak to you today.

Serena has already captured some of the breadth and diversity of applications of lithium-ion batteries. I suspect that everyone dialling in today is probably using a lithium battery even if they are not aware of it. They really are a ubiquitous technology, and one that has developed to a state of commercial maturity that supports its ubiquity. Whether we are aware of it or not, we are all using lithium-ion batteries every day. They are hugely scalable, from tiny batteries that might go into medical implants to really quite massive batteries that support grid-scale energy storage.

Almost all the batteries that we are discussing in that context are lithium-ion batteries, so the building blocks of the battery that goes into your mobile phone are the same as the building blocks that go into an electric vehicle and into some of these very large-scale, grid-scale batteries, so it is a flexible and scalable technology largely built on a common building block. As the technology has reached a level of maturity, it is possible that with lithium-ion batteries we will approach some of the theoretical limitations of that chemistry.

There are a number of road maps for how we can introduce advanced lithium-ion batteries by tweaking some of the components inside them. However, there is also increasing interest in what the post-lithium-ion-battery landscape looks like—there is consideration of lithium-sulfur batteries, sodium-ion batteries, solid-state batteries—and, perhaps on a longer time horizon, there is a whole portfolio of metal-air batteries that might also play a significant role.

We have a diverse portfolio of applications, so it is only right that we consider a diverse portfolio of batteries to support those applications.

Dr Jerry Barker: I am the CTO and founder of a start-up company in the UK called Faradion. You will hear a lot today about lithium-ion technology. Faradion is a sodium-ion battery company, so we fall into the group of cell chemistries that are beyond lithium ion. We have a world-leading position at Faradion in sodium-ion technology, which will be something for the future.

You asked about limitations. When you look at any battery technology, its limitations and what you need to do to make it commercial, it comes down to three main things: the cost—that is, the dollars per kilowatt hour; performance—we are always trying to push the envelope when it comes to lag time, cycle life, energy density and power density, which is also important; and safety. These are the things that keep us up at night working on battery technology. You have to complete the circle of cost, performance and safety.

I would add one more aspect to that, which is sustainability. One of the aspects that we push our sodium-ion chemistry on is that we should be more sustainable than lithium-ion technology.

Right now, as you are probably aware, the energy density of lithium-ion cells is improving at a considerable rate and the cost is coming down, so there are good moves. As those things improve, we will meet new applications.

Dr Melanie Loveridge: I am associate professor of electrochemical materials at WMG at the University of Warwick. I have no declared interests for the purposes of today's proceedings.

I would like to set a bit of background. The journey of development from the laboratory to the commercialisation of new materials in lithium-ion batteries can take a good 10 years or so. Very good developments that have been made with lithium-ion battery cells, such as the Panasonic 18650s and what Tesla has done, took a long time. From the point where you introduce an exciting new material to the point where you release a cell for sale is a convoluted journey that requires a lot of engineering and processing aspects as well as understanding the fundamental materials.

With regard to the limitations and performance, the diversification of the use of lithium-ion batteries compared with the initial portable electronics requirements means that the landscape is vast, so we now have performance clusters. Some of these are energy-driven, some are power-driven, but most applications are also cost-driven. One size will never fit all in batteries, which is important for when we are developing the road maps and defining the performance targets to reach net zero. There will be different requirements for each type of sector.¹

The Chair: One of you mentioned sodium ion. What are the technical issues related to developing sodium-ion batteries?

Dr Jerry Barker: I think I had better answer that one. What drove us towards sodium ion? Sodium is very similar to lithium in its chemical properties, as you are probably aware. It is heavier than lithium, which you might consider to be a bit of a disadvantage, but that does not make a lot of difference in the final device. What pushed us towards sodium ion was the potential for lower cost. Sodium versus lithium would be a lower-cost technology.

Then there is better safety. I mentioned the important ones earlier: cost and safety. What we are developing right now should also be a more sustainable technology. You have probably heard in the press that there are a lot of concerns about availability and where things are available, including lithium, copper and, in particular, cobalt. Our technology does not use any of those things, obviously. It does not use lithium, the obvious one, or copper or cobalt.

Finally, one thing that is important for us is that we developed a technology for sodium that could be built on existing lithium-ion lines, so you do not have to go off and develop a new manufacturing process. This is a technology that can be run on existing lithium-ion lines. We thought that was a good package of information on a good technology, and we are gaining a lot of traction in that.

When we started Faradion 10 years ago, we were pretty well the only show in town—indeed, in the world. We thought that we were taking a

¹ Limitations largely come down to firstly, the physico-chemical limits of the materials inside the electrodes that store lithium, and secondly how fast we can move the lithium ions to carry charge.

big lead. Now there is a lot of interest from all the lithium-ion manufacturers. People now consider that sodium-ion will be part of the future mix for different applications. It is one of the few technologies in batteries, I would say—I would say this, right, because I am the CTO of Faradion—where we are truly world leading.

Q21 Baroness Blackwood of North Oxford: Thank you. I have no interests to declare here, which I think also indicates that this is not my field.

I found it very helpful that Dr Loveridge talked about the time it will take to get from lithium ions to new materials. I would therefore find it quite helpful to understand the bounds that we are talking about when it comes to the potential performance of lithium-ion batteries, which are obviously the most common rechargeable batteries in use at the moment.

I am trying to understand the limitations and their potential performance, given the amount of research that is going on at the moment. I would find that very helpful. Perhaps, Professor Corr, you could give us a sense of the work you are doing at the Faraday Institution to improve performance as much as possible while we wait for other materials to come into play.

Professor Serena Corr: As my colleagues have said, conventional lithium-ion batteries have been tailored for high efficiency, long cycle life and relatively high energy density for specific use. However, energy density is limited by the number of available redox sites you have in the material and is hampered by degradation mechanisms that might preclude you from getting stable long-duration capacities. You can add to that the concerns that Jerry mentioned about cost, for example in trying to replace cobalt. You can think about lifetime and about materials' compatibility. All these things in the battery cell have to get on with each other if it will work properly. So delivering any candidate battery material demands strict crystal chemistry and engineering of composites. That is all informed by simulation and by fundamental understanding, which is key, as well as thinking about the techno-economics of sustainable and environmentally benign elements.

If we think about areas of research where you may improve the performance of lithium-ion batteries, you could look to improvements in the cathode, which is the positive end of the battery. The largest cost reductions will come from the cathode. There is an awful lot to be targeted here in terms of energy density increases. In the project that I lead—the FutureCat project on next-generation cathode development—we have highlighted three major areas that we think are crucial for improving the performance of lithium-ion batteries. They include things like controlling the morphology or the size and shape of your cathode materials. If you can generate compliant electrodes that are resistant to things like fracture, you will improve the lifetime of the battery.

Also, thinking about protective coatings, sometimes you will have reactions going on in your battery cell during charge and discharge or at

high voltages that can lead to side reactions that you really do not want to happen. That can reduce your capacity over time. So we look at things like new additives and coatings that might improve your cell's lifetime, safety and stability. Then, of course, building on the UK's world-leading history of discovery, we are trying to discover brand new cathode chemistries that rely more on earth-abundant elements and take advantage of higher-capacity materials. That is the cathode side.

On the anode side, one of the biggest challenges we face is that you cannot simply apply lithium metal as an anode in a liquid electrolyte battery at the moment. That is a challenge, because with lithium being so light we would have much lighter batteries and higher energy densities. Instead, we use a form of carbon called graphite. It works very well, but the challenge at high rates is that you start to build up lithium on the surface and it does not plate uniformly. Sometimes you can end up with things called lithium dendrites, which are potentially very harmful and give rise to concerns about safety and the risk of fires. So there is a lot of ongoing research into trying to develop and improve graphite anodes.

There is also the enticing opportunity to move to silicon-containing anodes. That could give you up to 10 times the energy density of commercial graphite. However, the challenge when you move to silicon is that silicon can change its volume by a huge amount—about 300%. You can imagine that, if silicon is doing that with every charge and discharge, you will end up pulverising the material and losing capacity over time.

So you can think about things like anode structure, going back to that idea of morphology. You can think about maybe nanostructuring your silicon to try to improve its structural integrity. Ideally, you would move to a completely lithium metal anode where you would not face the volume change but you still have to take care of the dendrite challenge. It is possible that that is where solid electrolytes, as applied in all solid-state batteries, could achieve that breakthrough.

Baroness Blackwood of North Oxford: My understanding—although it is a limited understanding, I admit—is that the underlying cause of dendrite growth is not well understood. Perhaps Professor Shearing and Dr Loveridge can tell us what the fundamental limitations of lithium batteries are that cannot really be overcome. Where does that boundary lie?

Professor Paul Shearing: When we think about defining the energy density of a battery, we would normally talk about energy density per unit weight, in watt hours per kilogram; or energy density per unit volume, in watt hours per litre. If you buy a good lithium-ion battery off the shelf today, you are probably looking at about 250 watt hours per kilogram. With more specialist manufacturing, you might be getting slightly more—300 watt hours per kilogram, perhaps.

There is a road map within the family of lithium-ion battery chemistries for tweaks to the materials and the design of the materials that might see the introduction of cells with 350 or 400 watt hours per kilogram, but beyond that you are probably looking towards what might be termed advanced lithium-ion batteries or next-generation batteries, such as

lithium-sulfur or solid-state batteries, which have metallic electrodes. We are approaching some of the fundamental limitations of lithium-ion batteries, but with the advanced lithium-ion and post-lithium-ion families of batteries there is a road map to increase substantially the gravimetric energy density—the watt hours per kilogram figure.

Using lithium metal as an electrode has been explored for a long time. Back in the 1970s, when people were first introducing lithium battery chemistries, many of them used metallic lithium electrodes, but it quickly became clear that, because of the irreversible chemical reactions that occur within the battery, the risk of dendrite growth during charging and discharging could lead to some catastrophic failures—and, indeed, to fires in some cases. So the industry moved away to different material sets and stopped using metallic electrodes.

However, there are benefits to using metallic electrodes in terms of the amount of energy that you can store per unit weight. So there are strategies by which we can protect electrodes. It is hugely important to make sure that they can charge and discharge effectively over long times without forming these harmful dendrites, or, if they do form a harmful dendrite, working out ways in which we can safely mitigate the catastrophic effects that can result from them.

There are a number of approaches to that. The first is a fundamental mechanistic understanding of how dendrites grow. The second is a material science approach to developing materials that can try to mitigate it. The third is an engineering approach: if we have cells where there is a risk of dendrite growth, can we have engineering and design approaches that will mitigate some of their negative impacts?

The Chair: We have about 45 seconds for Dr Loveridge, please.

Dr Melanie Loveridge: In addition to how much lithium can be accommodated in current anode and cathode chemistry as a limitation, you cannot avoid the reactivity of lithium. That is one of the fundamentals that cannot be eradicated. If we will develop lithium metal anodes, they have to be passivated and manufactured to a thin film quality. Those are fundamental aspects to be factored in.

Q22 Baroness Brown of Cambridge: I declare my interests. I chair the Carbon Trust, I am chair of the Henry Royce Institute for advanced materials, and I am a non-executive director of the energy company Ørsted.

I would like to ask about near-term, next-generation battery technologies, which I will define as beyond lithium-ion and things that might come into use within the next 10 years. I have a colleague who wants to look beyond that, so can you try and keep your answers to the things we might see in service in the next 10 years?

I would be interested to know the advantages of these technologies. For example, how does the sodium ion we have heard about take us to energy densities beyond the ones that Professor Shearing has already mentioned? I would be very interested in whether we have the right

innovation architecture in place to get these new technologies quickly into service. If not, what can we do to accelerate their move into service and production, as we have done for vaccines?

I would also be very interested in which UK companies are supporting this sort of research. Will they exploit the research and development you are doing, or are we doing all this research for overseas companies to benefit from?

I will start with Doctor Barker, since you already have a company in one of these areas.

Dr Jerry Barker: Thank you. Obviously, I will be a proponent of sodium-ion technology. You asked for the particular advantages over current lithium-ion technology. I think I mentioned those earlier. I do not think that sodium ion, because of its very nature, will be the highest energy density solution, but energy density is just one aspect. Battery technologies never provide all the answers to every question. If you can be competitive on energy density and power density, it does not have to be the highest energy density solution to have a number of applications.

Baroness Brown of Cambridge: What sort of energy densities are we talking about, compared to the numbers Professor Shearing gave us?

Dr Jerry Barker: It is very difficult, because energy density very much depends on how large the cell you look at is, so you have to make oranges and oranges comparisons. Our current energy density is about 160 watt hours per kilogram, and with a road map we think we can get to well over 200 watt hours per kilogram.

You may say that that number is lower than the numbers that Professor Shearing just mentioned, which are quite right for lithium-ion technology, but it is well ahead of some other lithium-ion chemistries and it is an immature science. We still have a long road to go on. We are very optimistic about this being a solution for a number of applications in the future.

Baroness Brown of Cambridge: Can you give me examples of the sort of applications we might see in the next 10 years?

Dr Jerry Barker: It is quite often easier to look at things like the displacement of lead-acid technology. We do not have a displaced top end of the lithium-ion market, but there are lots of other candidate applications. Right now, we are looking to replace lead-acid technology in mobility applications, forklifts, telecoms, and lots of other different applications. We are never short of markets. When you have no constraint on weight or volume, you can have large-format applications for renewable storage and grid storage as well, which will be very important for UK net zero as we move forward.

Baroness Brown of Cambridge: What advantages does it have for grid storage?

Dr Jerry Barker: For grid storage, it would be a lower-cost solution than lithium ion and it would be safer. One of the advantages we have over lithium ion is a safety advantage. You have probably seen instances on

YouTube and so on of EV battery fires. When you make a very big battery pack you have to put a lot of engineering solutions in to circumvent some of the safety challenges.

Baroness Brown of Cambridge: Can you keep your answer focused if possible, please?

Dr Jerry Barker: It is an intrinsically safer technology than lithium ion.

Baroness Brown of Cambridge: I would be interested to hear from Professor Shearing about other technologies that we might see in application in the next 10 years.

Professor Paul Shearing: I would like to mention lithium sulfur briefly as a possible next-generation battery chemistry, which I think will come online within that time frame. I entirely agree with what Dr Barker said. Depending on the application you are targeting, there are relative merits of energy density versus power density versus operating temperature window versus cost versus cycle life. There is a plethora of figures of merit that will mean different things to different applications.

One key advantage of lithium-sulfur technology is that it is intrinsically very lightweight. We are keen to wave the flag for the lithium-sulfur sector for that figure of watt hours per kilogram, because its light weight makes it appropriate perhaps for applications that fly. In the longer term, that might be commercial aerospace, but in the short term it is things like high-altitude pseudo-satellites and UAVs. Satellite applications are possibly a very attractive market for this intrinsically lightweight technology.

Baroness Brown of Cambridge: Do we have companies in the UK looking to take this technology to maturity?

Professor Paul Shearing: We do. I mentioned that I am the PI of the Faraday Institution LiSTAR project. We engage with a number of companies across the supply chain, from materials through to cell developers and manufacturers, all the way to applications. There is an ecosystem that spans the materials through to the application. There is a company called Oxis Energy, based in Oxfordshire, which makes, designs, and has an IP portfolio on lithium-sulfur technology.

Baroness Brown of Cambridge: When can we expect to see the first commercial application of it?

Professor Paul Shearing: I would be optimistic about the first commercial application happening relatively soon, but it is likely to be a niche application. In 2020, LG Chem demonstrated the application of a lithium-sulfur battery in an unmanned aerial vehicle. That was 400-plus watt hours per kilogram. At the moment, it is pre-commercial, but there is definite traction towards the commercialisation of those devices. It will probably start in niche applications, but we are optimistic that the traction those applications offer will bankroll the wider application of a broader portfolio of possible applications.

Baroness Brown of Cambridge: Doctor Loveridge, do you have any quick thoughts on how we might accelerate these things into wider

application?

Dr Melanie Loveridge: Certainly. There are enormous opportunities to develop supply chains from the materials and to scale up all the way through.² As we go into more demanding domains such as aerospace, there is a huge need to really think about cell format designs.³ This gets the best out of the materials regardless of the chemistry, whether it is a mature chemistry or an emerging chemistry. We need to innovate in electrode and cell design, module design and pack design.

Q23 **Viscount Hanworth:** What next-generation batteries might be developed in the longer term? We have already heard of lithium-sulfur batteries, but what about lithium-air batteries? What could their advantages be? What challenges in science and technology would have to be overcome in developing these next-generation batteries?

Dr Melanie Loveridge: Taking your example of lithium air, a lot of fundamental research needs to be concluded and developed before we move into realistically developing lithium air commercially. There is more of a pressing need to have an energy density perspective to further develop lithium metal anodes. They would currently be more realistic and achievable than lithium air.⁴

Professor Serena Corr: I echo what Melanie has said. Sulfur batteries, as Paul has mentioned, present enticing opportunities for high energy density, lower weight and lower cost compared to state of the art. There are also opportunities for multivalent batteries—for example, magnesium, zinc, or calcium—where there could be significant breakthroughs in energy densities. However, in those cases there are considerable fundamental questions that still need to be addressed through fundamental research into those technologies.

Beyond that, there are opportunities for things like organic batteries. Going back to Jerry's point earlier about sustainability, organic batteries present proved sustainability and lower environmental impact. We have a fantastic chemistry research environment in the UK, and we have the ability to tune properties through synthetic manipulation. But, again, fundamental research is needed.

Being able to manufacture these things at scale will be a significant challenge. Even moving to nearer-term things like higher-nickel-content cathodes raises enormous challenges in synthesis and handling. Trying to do that with the added control over particle architecture is an added challenge. We also require sustainable manufacturing practices that augment that journey to zero carbon, not just in battery assembly but in the synthesis of the battery materials that go into our cells.

² Supply chains are needed from the chemicals and materials, to the equipment for scale up and processing, all the way through to mass manufacture

³ There is also a need to optimise cells for specific devices.

⁴ This would be the case provided that the lithium foils can be stabilised and won't require impractical pressures and temperatures to operate.

If we are to reach the point where these near-term or next-stage chemistries will be applicable, we have to have continued and sustained fundamental research to inform whether solid-state batteries, for example, which have not been mentioned, could in the near term be a potential commercial opportunity. Whether or not you need specific manufacturing-at-scale requirements for those solid-state batteries, they are questions that fundamental science and engineering still need to answer.

Q24 Viscount Hanworth: What sort of improvements in energy density, volumetric and gravimetric density, durability, rates of charging and discharging, recycling potential and so on might ultimately be available? Can we quantify these things? I am mindful that last week we heard that solid-state batteries might afford a 50% increase. I am not sure in what or against what benchmark, but I think we need to quantify the improvements that we might ultimately expect.

Dr Jerry Barker: That is a tough question to answer, because it is so hard to quantify improvements that you require for things like solid-state batteries. I think we are all convinced that solid-state batteries may be one of the key technologies moving forward, just because going to a solid-state system offers such a big step in energy density.

Viscount Hanworth: What sort of proportion?

Dr Jerry Barker: You are looking perhaps at something like a 50% improvement in energy density. Professor Shearing mentioned that the chemistry we are currently using has a graphite negative electrode in lithium ion. We are replacing that graphite negative active material with lithium metal. We are going back to what we started with in the 1970s.

The difference is that instead of using a liquid electrolyte, which creates a very poor interface that can then create dendrites and higher surface area lithium, if you use a solid-state electrolyte perhaps you can stop that higher surface area lithium problem arising and you can stop the dendrite growth. Those are very difficult problems to solve. You have probably seen the press releases, but some companies almost give the impression that a lot of these things have been solved. Our true belief is that this is quite a long way from being commercialised, perhaps four or five years at minimum.

Viscount Hanworth: Can I ask a simple question? Does the rate of delivery correlate directly with the energy density—that is, the rate of charging and discharging?

Dr Jerry Barker: It depends. You can run cells at different charge and discharge rates. Something that always concerns us is the rate at which you can charge and discharge a cell. Generally, though, the higher the capacity of the electrodes, which is what you are trying to maximise, the more slowly you will have to discharge the cell. There is a trade-off, in fact. As electrochemists, as battery scientists, we are always trading energy with power. It is a well-known relationship—the Ragone relationship.

The Chair: I regret this, but please keep your answers brief if you can, although of course we want to hear the answers.

Q25 **Lord Kakkar:** I turn to the question of the challenges facing the scaling of new battery technologies and materials from lab to wider manufacture and then broad population usage. Please summarise for us the steps that one has to go through to scale up new technologies. What are the scale-up challenges for some of the technologies that we have heard about, such as solid-state, sodium-ion, lithium-sulfur, metal-air, and so on?

Dr Melanie Loveridge: There is an issue when you start looking at new materials and chemistries and more fundamental early-stage research. I do not know whether you can see this. This is a small research-scale coin cell, that is very easy to produce. However, when you want to further develop materials to prototyping, whether anodes, cathodes or electrolytes, you start having to factor in processing and more engineering aspects. This is in parallel to the understanding properties and the structure of the active materials. One of the central paradigms of materials science are the complex interdependent relationships between the properties of a material, its structure, and the processing parameters it undergoes to achieve the ultimate device performance.

It is critical to be mindful of these when you go from the very low material TRL to entering into the manufacturing readiness levels. Keeping those aligned and not having a lag period between them is critical. Quite often, people focus on the fundamental chemistry and the material properties, and then overlook the engineering and processing efficacy as key stages in creating commercial industry-relevant cell formats.

Professor Paul Shearing: I echo exactly what Dr Loveridge has said. The journey from the lab to the market can sometimes be long and tortuous. Obviously it took a long time to go from the discovery of some of the fundamental materials of lithium-ion batteries in the late 1970s through to their mass-scale manufacture. Embedding enough engineering understanding into the fundamental materials discovery and design process so that chemists at the bench discovering new materials are cognisant of and thinking about the scale of challenges really early on in their research is key to being able to accelerate that journey of commercialisation.

Of course, we can learn a lot through what has already been achieved in the lithium-ion battery sector and re-apply that to the next generation of battery chemistries. We are also equipped with more advanced tools and techniques, both experimental and modelling, that will also help to accelerate that journey. We cannot wait as long with this portfolio of next-generation battery chemistries, so, whatever happens, that journey needs to be accelerated, and we need that translation from the coin cell to the electric vehicle battery to be much faster. We are equipped and we have an ecosystem in the UK to support that, so I am optimistic that that is possible.

Lord Kakkar: Could you give a brief description of that ecosystem? How confident can we be that we have that multidisciplinary approach properly

supported and co-ordinated to deliver what you describe?

Professor Paul Shearing: I will talk briefly about the Faraday battery challenge, which has three key arms. The first is the Faraday Institution, delivering basic research, mostly in universities, although we are closely collaborating with industry. The second is collaborative R&D co-ordinated by Innovate UK, which is industry-led predominantly research projects. The third is the development and construction of the UK Battery Industrialisation Centre.

That nicely maps on to those technology readiness levels and illustrates how it is possible, under the one umbrella of the Faraday battery challenge, to integrate from very low TRLs of materials discoveries in universities and to provide that pipeline through translating research into the companies, through to commercialising, developing and deploying these technologies at manufacturing scale.

Q26 **Lord Kakkar:** Professor Corr, can I turn to your view about which of the emerging battery technologies appear to be the frontrunners in this scale-up race?

The Chair: In the UK.

Professor Serena Corr: In the UK, the things that are closest to scale-up where we have a competitive edge are next-generation lithium cathodes, sodium-ion and solid-state batteries.

To go back to what was required to get those things to where they are now, a sustained commitment to making funding basic science and basic research is critical. Each of those areas requires answers to very challenging questions, and that takes time. Deepening our collective understanding of the fundamentals of battery chemistry in mechanisms, thermodynamics and kinetics informs and drives innovation. As those battery chemistries emerge and become scaled up, the sustainability challenge is a particularly complex one that we have to deal with if we are to get to net zero. The questions of element abundance and sustainable manufacturing processes, which Melanie has mentioned, need addressing now. The key innovations that we are making today will shape what happens in 2030, which will be a stop on the road to 2050.

On the commercialisation question, to echo something that Paul said, being able to facilitate the continuity from the low to mid TRL-level research that is going on at the bench and having some kind of national commercialisation framework for fast IP capture and translation would be really valuable, particularly in the battery space. This is a really fast-paced field with significant patent activity, so having some sort of national standard commercialisation pathway would be really helpful.

Q27 **Lord Kakkar:** Dr Barker, what do you see as the principal scale-up challenge for sodium-ion batteries in the next five years?

Dr Jerry Barker: The scale-up challenge is taking it from where we are now, which is the prototype level, to full manufacturing. Right now, one of the challenges that we have is that we as a UK company prefer to do

this in the UK, but all our larger-format cells are put into demonstration units in China. Our biggest problem is that we would prefer to do it in the UK somewhere, but there is not the infrastructure, so we are forced to do it quite a long way away, which does not make it easy to co-ordinate the work. As I say, we would much prefer to do it in the UK.

Lord Kakkar: To be clear, this is because of a lack of infrastructure for taking that scale-up pathway forward?

Dr Jerry Barker: I have been in the lithium-ion industry for 30 years now, and my belief is that the UK is world-class in fundamental, intrinsic, basic research. What we have not been good at until recently—at least we are doing the joined-up bit now—is the scale-up and commercialisation end of things. Companies like Faradion, which has 16 employees, are forced to look elsewhere to do this kind of scale-up at a decent cost.

Q28 **Lord Krebs:** In a way you have partially answered my questions, but I will check that I have understood. If we ask which next-generation battery technologies have the most realistic prospect of widespread use in time to contribute to the 2050 target of net zero, I understood Professor Corr to have said that there will be three possibilities in the UK: improvement to the lithium-ion battery, the development of the sodium-ion battery, and possibly the development of solid-state batteries. I would like to check that that is the list that you are adhering to.

The second part of my question comes back to what areas the UK has a comparative advantage in. All three of you have stressed both the quality of our basic science and the co-ordination under the Faraday battery challenge. I wonder about the scale of that. The Faraday battery challenge is £318 million, which seems miniscule in relation to the size of the problem that you are trying to address. Could you comment on that?

So there are two parts to my question: have I understood where the likely developments are that will contribute to net zero by 2050, or have I missed something; and is the Faraday battery challenge really at the right scale to put us at the front of the pack?

Professor Paul Shearing: Thank you for the summary. I would also like to highlight the role of lithium-sulfur batteries, as I mentioned. As a PI of the LiSTAR programme developing lithium-sulfur technology for the Faraday Institution, it would be remiss of me not to highlight the important role that we think lithium sulfur can additionally play. However, you nicely capture the portfolio of options: advanced lithium ion, lithium sulfur, sodium and solid state. There is a whole portfolio of possible options, but they are at the more fundamental research question-level with very low TRLs.

I am sorry. What was the second part of your question?

Lord Krebs: Is £318 million a big or a small number?

Professor Paul Shearing: Clearly it is a significant amount of investment, but I think you have to compare it with the international context. Off the top of my head, the investment in Germany is an order

of magnitude larger. The Faraday battery challenge has demonstrated that that investment of £300 million or so has catalysed a lot of activity in universities and industry to try to address some of the scale-up challenges that Dr Barker has highlighted. If we want to retain and grow our international competitiveness, it is likely that the scale of funding will need to increase to be commensurate with what is being achieved in Germany and echoed in many countries around the world. That scale of investment is quite substantial elsewhere.

Professor Serena Corr: I was also going to mention lithium sulfur. To highlight something that we have not mentioned so far, there is an inherent risk in considering battery chemistries in isolation. As a research community we are increasingly moving away from the siloing of research activities for that reason: because you can miss opportunities for cross-fertilisation. For example, in one of the chemistries that could be very important as a realistic prospect for 2050—solid-state batteries—our new solid-state electrolytes still require a cathode material that is selected and tailored to deliver the full performance of that solid electrolyte. Developments in new battery technologies could act as signposts to the next-generation battery technologies that also contribute to the 2050 target. To echo what Paul said, I think we have an opportunity to realistically target lithium sulfur as well as solid state, provided that we continue to push our understanding of those technologies.

You asked about competitive advantage. We are well positioned in the UK, with the announcement of the first gigafactory site for Britishvolt and, as Paul mentioned, the UK Battery Industrialisation Centre. In addition to delivering leading research, the Faraday Institution also provides very high-quality training for PhD students and postdoctoral researchers. There are hundreds of them now who will be the next generation of scientists and engineers.

Also required is a wider plan for skills training and apprenticeships. As a research base in the UK, we also have the extraordinary benefit of having access to world-leading state-of-the-art facilities at the Diamond Light Source and the ISIS Neutron and Muon Source facility. These allow us to perform intricate experiments that inform mechanistic understanding. We have been doing that for decades and building on that fundamental understanding, as well as more recent investments in high-performance computing facilities that allow us to predict solutions.

The scale of investment is not as large as some other countries—fair enough—but it is the largest investment that has gone into battery research in the UK, and look at what we are doing with it. The Faraday Institution evidences that we have a research base that embraces collaboration across academic disciplines and with industry partners, and that collaborative effort represents a real competitive advantage here in the UK. I support what Paul said about emerging chemistries that will require continued support and investment.

Lord Krebs: Thank you. Am I out of time, Chair?

The Chair: You have one minute left.

Lord Krebs: Would anybody else like to add anything briefly?

Dr Jerry Barker: I concur with what my colleagues have just said about priorities in the UK. I would add that the one thing we should be looking at—actually, we are looking at it in the Faraday Institution—is new manufacturing methods for making these cells. Quite often, you can make bigger incremental improvements in the way you put these cells together. If you look at the way we make lithium-ion cells now, the manufacturing methods literally have not changed for 30 years. Ways of making better electrodes and better use of them can make a big difference, and we have some world-leading research in that area.

Q29 **Baroness Manningham-Buller:** As the panel knows, we are looking not just at batteries but at fuel cells. You have all mentioned the degree of co-ordination across scientists, interfaces and so on, and the Faraday challenge promoting this. Do any of you wish to comment on the thought that we have been paying more attention, as we heard in our first evidence session, to the development of batteries over that of fuel cells? Is there scope for greater co-ordination of work between these two areas and disciplines?

Professor Paul Shearing: I understand that, in the following hour, you will also be talking in more detail about fuel cells. The important thing I want to highlight is that, just as many battery chemistries are complementary to each other, I strongly believe that fuel cells and batteries are complementary to each other. If you look at many examples from the vehicle sector, there is clear evidence of how batteries and fuel cells can work in perfect harmony.

In respect of the funding, the current zeitgeist among research funders has probably channelled money more towards batteries, perhaps at the expense of fuel cells. I would certainly be in favour of increasing the funding for fuel cells and the hydrogen economy in general. Most people who are giving evidence today will probably agree that there is periodic oscillation in funding and technologies go in and out of fashion and that this sort of oscillation makes it quite challenging to plan strategically for research programmes, because there is a loss of momentum in the research that is done, and a risk of the loss of the skills base.

From a technical perspective, a lot of people—I hesitate to say most people—would recognise the complementarities of batteries and fuel cells. Achieving a funding situation that recognises the significant contribution that they can both play would be very welcome.

Q30 **Baroness Manningham-Buller:** I would like to move on from that. You are thinking about equal funding but—perhaps I can ask Professor Corr about this—what about co-ordination between research? You mentioned working together and possible hybrid manifestations. Is there sufficient overlap in the research of these two groups?

Professor Serena Corr: In some instances, the answer is yes. The Faraday battery challenge has enabled the opportunity, as you mentioned in your question, to efficiently bring together multiple research

communities to tackle a common challenge. We have a common aim that unites us. That kind of co-ordinated approach can really accelerate progress. Echoing things that Paul has said, that needs to sit alongside additional research and development that is funded through research councils to make sure that we are continuing to capture new discoveries. Because a co-ordinated effort draws in researchers from multiple disciplines, there is probably even more potential now for greater co-ordination between the battery and the fuel cell research and development communities.

There is possibly a pressure on people to pick winners in the energy storage and conversion space. I am not sure that I really agree with that. It is important to pick the technologies that you think have the greatest chance of success and make sure that they have the best support to be able to achieve it. However, in your first evidence session, you heard that there was perhaps a stagnation in the funding for fuel cells, and that probably needs to be addressed. As Paul says, there are enormous opportunities for hybridisation across energy storage and conversion devices, where we borrow inspiration from the world around us and we have these two things happening simultaneously.

Baroness Manningham-Buller: Do Dr Barker or Dr Loveridge have any examples of moving beyond opportunities to actual co-ordination between these two routes?

Dr Jerry Barker: That is an interesting question. There are lots of complementary devices moving forward, as you can imagine, between hydrogen and batteries. As Serena mentioned, one is a conversion device and one is an energy storage device. Every hydrogen fuel cell car also has a battery involved; it is not just in isolation. I am not quite sure how co-ordinating and working together would work. Perhaps I will leave that question for someone else.

Dr Melanie Loveridge: In the absence of any clear energy policy on one or the other, I see them as complementary—to reiterate what Professor Shearing said. Another interesting consideration is that there are commonalities in some of the research elements of developing components in both of them.⁵ Ultimately they each have distinct advantages and disadvantages per application. That factor needs to shape the strategy for where the research on future development and funding would be deployed.

Baroness Manningham-Buller: What is your view of Professor Corr's idea about the pressure to pick winners? Is that complicating our progress in this area?

Dr Melanie Loveridge: Because of the diverse domain of electrification, it is difficult to have a clear-cut, prioritised list. It has to be market-driven.⁶

⁵ Many researchers have spent time in both battery and fuel cell developments, and so a growing skillset is already there.

⁶ However, all elements of the technology ecosystem need to be balanced and joined up (research, industry—supply chains and manufacturing—and Government).

The Chair: Lord Krebs has a supplementary question from earlier, following on from the question asked by the noble Baroness, Lady Brown. You have one minute left.

Q31 **Lord Krebs:** It follows on from the questions asked by the noble Baroness, Lady Brown, and the noble Viscount, Lord Hanworth, in fact. In a second or two, can you comment on developments in linking supercapacitors and batteries?

Professor Paul Shearing: Supercapacitors deliver phenomenal power density. They deliver energy very quickly, but they do not store a lot of it. If you are interested in applications where you have a need for a very high acceleration for a very short period of time, supercapacitors might be advantageous technology. Obviously, they also recharge very quickly.

However, if you need to store energy—for example, to get vehicle range—again, supercapacitors will need to be hybridised with something to give that range, such as a battery or a fuel cell. Across the piece of supercapacitors, batteries and fuel cells, there are intrinsic advantages in the ability to store or convert energy, and in balancing this power versus energy debate. The intelligent hybridisation of those three devices provides a compelling opportunity to address the shortcomings that each individual device intrinsically has. The intelligent hybridisation of supercapacitors, batteries and fuel cells will actually mean that they are greater than the sum of their parts.

The Chair: What about redox flow?

Professor Paul Shearing: Redox flow batteries are an attractive technology, probably for grid-scale energy storage at relatively large scales. They have the advantage of scalability into the range of hundreds of megawatt hours. They operate in the space between a hydrogen fuel cell and a battery. They have an intrinsic ability to decouple the energy stored, which is dictated by the size of the tanks that you store stuff in in a redox flow battery. Also, the power that it delivers is dictated by the kinetics of the reaction and the rate of reactant flow through the battery itself. It is an interesting technology, but it is mostly suitable for larger-scale and stationary applications.

The Chair: We are bang on time. Thank you, all four of you, for making time to come today. We appreciate it very much. It absolutely was an informative session.