HOUSE OF LORDS

Select Committee on Science and Technology

Corrected oral evidence: Role of batteries and fuel cells in achieving Net Zero

Tuesday 9 March 2021

10 am

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

Evidence Session No. 1 Virtual Proceeding Questions 1 - 19

Witnesses

Professor Nigel Brandon OBE, Dean of the Faculty of Engineering, Imperial College London; Professor Mauro Pasta, Associate Professor of Materials, University of Oxford; Professor Pam Thomas, CEO, Faraday Institution, and Pro-Vice-Chancellor for Research, University of Warwick; Amer Gaffar, Director, Manchester Fuel Cell Innovation Centre, Manchester Metropolitan University.

USE OF THE TRANSCRIPT

Examination of Witnesses

Professor Nigel Brandon, Professor Mauro Pasta, Professor Pam Thomas and Amer Gaffar.

Q1 **The Chair:** Good morning, everybody, and thank you for joining us today. Before we start, there are one or two housekeeping matters. I have apologies from Baroness Blackwood, but I am paired with her and will take the first question anyway. Lord Winston has dodgy internet, so he may drop in and out. Baroness Sheehan may be caught out by a telephone call, but we will deal with that. I will follow all the other instructions that you sent me.

I give a warm welcome to our expert witnesses today and to our specialist adviser, Professor Grey. Good morning, Professor Grey, and thank you for joining us and helping with the rest of the inquiry. Our expert witnesses are Professor Brandon, Mr Gaffar, Professor Pasta and Professor Thomas. Thank you all very much for making time to help us with our inquiry. You are the first set of witnesses, so you are setting the temperature for this inquiry. Our inquiry is about using science and technology as it refers to batteries and fuel cells and their contribution to decarbonisation in the United Kingdom.

The meeting is being broadcast on the parliamentary channel on the internet, so you cannot have a private conversation; it will be recorded. Committee members, please declare your interests before you ask a question. Before we start, can I ask all the witnesses to say who they are for the record?

Professor Nigel Brandon: Good morning and thank you. I am dean of the faculty of engineering at Imperial College London. I am director of the UK Hydrogen and Fuel Cells Supergen Hub, which is the major investment by the research councils in hydrogen and fuel cells. I declare my interest: I am also a founder of two companies in the sector, a fuel cell company and a flow battery company.

Amer Gaffar: Thank you for inviting me. I am the director of the Manchester Fuel Cell Innovation Centre, based at Manchester Metropolitan University. We were opened officially only in 2018, by our chancellor, Lord Mandelson, so we have been supported by a number of academics, including Nigel, in achieving our success to date.

Professor Mauro Pasta: Good morning. I am an associate professor at the department of materials at the University of Oxford. My main research interests are in lithium ion batteries, and in technologies beyond lithium ion batteries in particular. In that sense, in the past three years I have been leading the solid-state project at the Faraday Institution, which is part of the Faraday battery challenge. I declare a conflict of interest in that I am also a co-founder of a start-up company working on lithium batteries.

Professor Pam Thomas: Good morning, everybody. I am the pro-vice-chancellor for research at the University of Warwick and the recently appointed CEO of the Faraday Institution, which convenes the national battery project, supported through the industrial strategy challenge fund and the EPSRC.

Q2 **The Chair:** I have no interests to declare in relation to this inquiry. My question is about the contribution that batteries and fuel cells are making in the United Kingdom just now.

Professor Nigel Brandon: I will comment on fuel cells. I have colleagues who will comment on batteries.

In the fuel cell market in 2019—the year we have the best data for at the moment; we should see 2020 data soon—1.1 gigawatts of fuel cells were sold globally. About 70,000 products accounted for the greatest number of sales of units, 45,000 of which were purchased by consumers in Japan to heat and power their homes. About half the total power capacity was represented by the sales of cars, trucks and buses in Asia.

In the UK, at the moment, the contribution is relatively small. We have some demonstration projects, particularly fuel cell bus projects in Scotland and London, and there are some demonstration fuel cell heat and power units in a small number of homes, but at the moment I would say that the contribution in the UK context is small. It is more about the potential, but we are seeing it making a contribution in other parts of the world where there is a stronger level of support for their deployment.

The Chair: Who would like to comment on batteries?

Professor Mauro Pasta: I can make a general comment and I am sure that Professor Thomas can follow up on the battery side. I would like to make a general comment related to both batteries and fuel cells. They are both energy storage technologies, so they can contribute towards decarbonisation in a manner that is proportional to the renewable energy sources that fuel them. If you are fuelling them with a lot of renewable energy sources, that will mean that they will contribute quite actively.

In terms of the market for batteries in the UK, last year I believe that over 100,000 vehicles, of about 1.6 million cars, were purely electric, so full EV[1]. That is a big increase, over 180%, over the previous year, so that contributed quite actively.

Professor Pam Thomas: In a similar vein to the way Professor Brandon spoke about fuel cells, globally we are currently providing about 300 gigawatt hours through lithium ion technology in batteries. In order to meet the requirement for electric vehicles, by 2030, this is expected to increase that by roughly seven times to about 2,000 gigawatt hours. Of that, about 70% would be for passenger EVs, as well as other types of electrical transport such as electronic buses, consumer electronics, stationary storage—storage for the grid—and commercial electronic vehicles.

The Chair: So it would be correct to say that the contribution made by

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[1] The following link was provided after the evidence session: https://www.smmt.co.uk/vehicle-data/car-registrations/ [Accessed on 20 March 2021]

batteries and fuel cells just now in the UK compared to other countries is small, but that most of it is in electric vehicles. Is that correct?

Professor Pam Thomas: Yes. At the moment, the contribution is 60% to 70% in electric vehicles from our current lithium technologies. In the future, it will be about 70%, but we need to have seven times as much as we are currently producing and using.

Q3 **Baroness Brown of Cambridge:** The extent to which batteries and fuel cells are interchangeable technologies is an interesting question. Should we see them in very separate applications?

Amer Gaffar: We have supported over 80 small to medium-sized enterprises that are involved in fuel cells and batteries. They are looking at what the market is doing and saying, and whether it is following one technology or the other. We are finding that, as we move towards an energy transition, these technologies are equally important. More and more organisations that we are supporting want to involve both technologies, whether that means one or the other being the dominant power train in a vehicle. In the market, they are seeing most of the vehicle manufacturers following one or other of the technologies.

Baroness Brown of Cambridge: I now turn to Nigel. You have been in this area for many years now.

Professor Nigel Brandon: Yes, indeed, and I have the scars to prove it. They are likely to play different roles in different applications. A battery, as has been articulated, is an energy storage device; you put energy in and then you pull energy out of it. A fuel cell is an energy conversion device; you put a fuel in and you generate DC power.

They both have potential application in electric vehicles, whether battery electric or fuel cell electric, but it is much more likely that fuel cell electric, operating most likely on hydrogen—we could also discuss ammonia as a hydrogen carrier, particularly for very large vehicles—will find its application when energy requirements are high. These will be more likely in larger vehicles, off-road vehicles, buses or long-distance trucks. It is much more likely that the battery solution will lend itself to smaller energy requirements, such as with lighter-duty vehicles, urban vehicles and so on. Of course, there will be an overlap somewhere in the middle.

As Pam has articulated, batteries will also play a role in supporting the transition to a more renewable energy system, managing the intermittency of supply and demand over periods of seconds, minutes, hours, days and so on. Energy storage matters there. Fuel cells will have a role to play in providing heat and power, or certainly power, off a range of fuels for stationary applications. In that sense, they will play complementary roles. One is a flexibility technology; the other is a very efficient power generation technology. In transport you will see some overlap, but also I expect segmentation of the market, depending on the vehicle energy requirements.

Q4 **Baroness Brown of Cambridge:** I am interested to hear what advances we can expect to see in battery and fuel cell technologies in the short term, the next five years; and in the long term, which is perhaps 15 years, although I am happy for you to define the long term as you think appropriate.

I am particularly interested in what sort of valuable incremental changes we will see. Where might there be some step changes? Where are we already getting close to theoretical limits, if anywhere, and so not expect to continue to see improvement? I am particularly interested in efficiency and energy density.

Professor Pam Thomas: Lithium ion battery manufacturing is what we have at the moment for the mass market. From 2020, projecting to 2035, we will need to reach lower battery pack costs of about $100 per kilowatt hour for those types of application. That is difficult and beyond the current technologies, so we need to move into next generation technologies to get the kinds of power densities and energy densities that we require to do this at scale across the applications. If I can concentrate on automotive, that is particularly for the passenger vehicle market. On that timescale, it is clear that we have to transform from the current technology to next-generation technologies to meet that kind of requirement. We are coming up against the limit.

From a UK perspective, we will not overtake existing manufacturers of the current lithium battery technology. It would serve us better to leapfrog the current technology and look at where we might be able to have a world lead in establishing next-generation technologies. My colleagues, such as Professor Pasta, are very well placed to talk further about that.

Baroness Brown of Cambridge: Are you saying that, apart from a bit of cost reduction, we will not see any developments in the next few years that will improve on pretty much what we have at the moment?

Professor Pam Thomas: There are incremental developments. We can still improve the existing battery technologies based on lithium. Indeed, we have projects in the UK, under the auspices of the Faraday Institution, aimed at producing those incremental changes. However, if we want the step change associated with getting to net zero by 2050, we will need the next generation of battery technologies.

Baroness Brown of Cambridge: What is a valuable incremental change? Is it 5% or 10%?

Professor Pam Thomas: That is a very good question, and I think you would get a different answer to that from the different sectors. Anything that improves the properties of existing batteries by 10% to 50%, bringing the cost down, giving us longer range for the same cost of battery, or bringing the size down, is worth doing. Clearly, there will be a cost saving to the consumer. There is also a behavioural aspect to this in that consumers need to take up this technology and use it. The incremental changes are worth while, and that is what we will have in the short term. We need to keep pushing that forward in order to improve what we have at the moment. If we will make the step changes that we require for net zero at 2050, just pushing the incremental envelope will not be sufficient.

Baroness Brown of Cambridge: Professor Brandon, where do you see the performance of fuel cells going in the short and the longer term?

Professor Nigel Brandon: Fuel cell technology works. We have a set of materials and devices that are being run in service now, with over a gigawatt sold in 2019. There are some similarities to the battery piece that are about manufacturing scale. Fuel cells today are still made in relatively low volumes. That inhibits their cost efficiency, so we need to get to the gigafactory equivalent scale in fuel cell manufacturing, as we do in other electrochemical technologies, such as electrolysers, and as we have in lithium ion. That will drive down a lot of cost.

That is not to say that there is no room for innovation. The target platinum group metal loading—the amount of platinum you have in a low-temperature fuel cell in a car, for example—needs to be about the same as in a catalytic converter today for a conventional gasoline engine. At the moment, it is higher than that, so there are opportunities to innovate there. There will always be a need to drive up performance in terms of both efficiency and lifetime. That will be an underlying requirement as we go forward.

We also need to remember that it is not only about the fuel cell, but about the system the fuel cell operates in. It is the balance of plant components—the compressors, the blowers, the heat exchangers, the hydrogen sensors if it is a hydrogen fuel cell, and everything else that is needed. The most expensive part of a hydrogen fuel cell car today is the hydrogen tank, so there is room for innovation in how you carry the fuel and so on.

I come back to manufacturing scale. For this industry to compete globally, we need to be capable of putting product out at the right price with the right warranties. That is about manufacturing scale and innovation. Fortunately, the UK is well placed in the fuel cell sector. It has leading companies in both high and low-temperature fuel cells. They are attracting inward international investment, which is a great base to move forward from.

Baroness Brown of Cambridge: The short-term issue for fuel cells is learning by doing in order to deliver.

Professor Nigel Brandon: There is definitely learning by doing, but that is not to say that there is no room for underlying science. A lot of the learning by doing will require advances in science and the application of science to understand, for example, how we double the lifetime under a particular operating mode and so on. These will all impact on the practical implementation. There will be a strong coupling there.

Baroness Brown of Cambridge: My colleague Viscount Hanworth wants to probe more into the exciting new technologies that Professor Thomas has referred to.

Q5 **Viscount Hanworth:** I was wondering what a step change in battery technology could consist of, but maybe I can ask some more humble questions.

I have a composite question about lithium versus sodium, and then one about solid-state batteries. I presume that, on most criteria, lithium ion batteries are the most efficient, because lithium is the lightest metal and, therefore, presumably its ions are most mobile. There is a question about the supply of lithium, which is mined mainly in the Andes and some of it in North America. Lithium salts are also present in ocean waters. One question that occurs to me is whether it could be economically extracted from brine.

Sodium is four times heavier than lithium and, therefore, presumably its ions are less mobile, but sodium salts are plentiful. Does the advantage of the cheapness of sodium weigh against the lesser efficiency of sodium ion batteries?

That is a composite question, but you can see the two things hang together. Looking at the periodic table, what about beryllium?

The Chair: Is it sodium or lithium?

Professor Mauro Pasta: That is a very good question. Let me take it one step at a time. In terms of improvement over lithium ion batteries, as Professor Thomas mentioned, the current intercalation chemistry, which the UK heavily contributed to developing and inventing, has been around for 40 years now. It is approaching a theoretical limit: the physical chemical limit. There is so much we can do in cost reduction simply by optimising economies of scale. If we want to take the next step, we need to look at more energy-dense technologies.

In the next five years, we will provide some incremental improvements over this current technology by incorporating, for example, more silicon in graphite negative electrodes, decreasing the cobalt content and increasing the nickel content in cathodes. That could be quantified as about 10%. If we want to get to the next level, more than 50%, the ultimate strategy is to implement the use of lithium metal. There are different avenues to achieve that. You have probably heard of lithium-sulfur batteries, where you have a lithium metal negative electrode and a sulfur cathode. There are more traditional lithium transition metal oxide cathodes and, looking forward, even lithium-air.

The problem which these three technologies have in common is that lithium does not really like to plate uniformly. It tends to plate in a very rough fashion that results in very low cycle lives and some safety issues associated with organic liquid electrolytes. That is why there is a lot of attention and a lot of interest in solid-state batteries moving forward. In a solid-state battery, the liquid electrolyte is replaced with a solid. By doing that, we can in principle incorporate lithium metal, which has very high-energy density, and therefore increase energy density. At the same time, we can decrease charging times substantially—some estimate even below 50 minutes as a key target—and improve safety.

If you put the three concepts of increased energy, decreased charging times and improved safety together, it is no surprise that every automotive company is looking quite heavily into solid state right now. The timeline for solid state is a tough question. There are more optimistic expectations for the 2030s. Some are a little later—the 2040s. Some are a little more pessimistic and say that it will be difficult to get solid state produced at cost. Therefore, at the Faraday Institution, we are developing the fundamental science that will allow us to tackle some of these problems.

Sodium versus lithium is a slightly different question. It is a problem of the supply chain and the supply and demand of raw materials. As the demand for lithium ion increases, this will definitely be a problem. Having an alternative to lithium could be advantageous for some applications. It comes at an energy penalty because of the concepts mentioned earlier. Sodium is heavier and does not diffuse as quickly in transition metal oxide. It is good to be ready to have back-up alternatives to lithium ion, just in case supply and demand is problematic.

Q6 **Lord Kakkar:** I should declare my interest as professor of surgery at UCL and a member of the advisory board of the Royal Society.

I want to turn to the practicality of how quickly UK battery and fuel cell manufacture can be scaled up to meet the demands that we have touched upon. Is it really feasible in the timeframe considered, having heard already in this session about the need to leapfrog to other potential technologies? How will it be managed practically?

Amer Gaffar: I will provide evidence of how we are working with some of these businesses. They are innovating to various degrees when it comes to the fuel cell itself, but less so on the battery side, where they tend to work more with our additive manufacturing guys, trying to fit a battery, using 3D printing techniques, around different mechanisms.

As my colleagues have described, fuel cell technology works, and it works very efficiently. To get it to the level that we need, we have to support the investment decisions that are being made by our partners in, for example, our city region about public transport and heavy goods vehicles. They are going for the technology that they know, which is battery electric, because the infrastructure is there. They need support to understand the role that hydrogen and fuel cells can play. By linking hydrogen and fuel cell projects together, we will find that scale quite quickly.

Lord Kakkar: Professor Thomas, do you think it is reasonable to consider that production of batteries and fuel cells is sustainable using our current technologies and production processes?

Professor Pam Thomas: We are aware that there has already been interest in establishing a gigafactory in the UK, in Blyth in the north-east, by Britishvolt. We also have a scale-up facility—UKBIC—that has been produced as part of the Faraday Battery Challenge, which is a UK industrial battery centre. We have a large number of projects that are looking to transfer novel chemistry into the manufacturing space via the scale-up route. We have the building blocks in place to look forward to having gigafactories in the UK, with battery production for a UK market.

One of our *Faraday Insights* reports said that we would need seven gigafactories to supply the UK market by the year 2040, and that we would expect to see two or three established in the UK by 2030. That is an achievable ambition. It is a plan which industries in the UK are working to and which we are providing the workforce for—at the high level, through 131 PhD students, who are currently being trained in battery science—and then scaling down. I know there will be a question on this later, so I will leave my remarks on skills for then. There is a large effort in the UK aimed at having this scale of production. It is a realistic ambition.

Lord Kakkar: You speak about the fundamental science, the training, the PhD students and the building blocks that are in place. Is there anything missing in that pathway that should be an area of greater focus in order to ensure that the ultimate ambition of increasing production facilities can be delivered?

Professor Pam Thomas: It is very important to maintain the long-term vision from the research and industrial collaborative R&D in order to make sure that we do not lose the great platform that we have built over the past few years. If we give way to short-termism in our scientific research funding, our industrial collaboration research and development funding, we could lose the opportunities that we have built. We have fantastic science in the UK. We are building a very highly trained workforce to bolster the manufacturing industry. We need to make sure that we keep the faith and momentum towards the aim, which is to have these large manufacturing abilities within the UK.

Q7 **Lord Krebs:** I would like to declare two interests. First, I am an adviser to Drax, the electricity company. Secondly, I am a fellow of the Royal Society and have been working on a number of reports about net zero for the Royal Society.

I have two points following on from Lord Kakkar's question. The first is for Nigel Brandon. We have heard from Professor Thomas about batteries. Could you tell us similarly about the scale-up of manufacture of fuel cells? The second point, which is probably for either Professor Thomas or Professor Pasta, is about the sustainability of materials, which Lord Kakkar asked about but I did not get a clear answer.

Professor Nigel Brandon: We are in a slightly different position on fuel cells, in that we have not offshored our fuel cell manufacturing facility to Asia. We have companies such as Johnson Matthey, which has been operating a scaled fuel cell fabrication plant for some years now. We are building capacity. The company I helped set up, Ceres Power, is building a factory in the UK at the moment and there are other innovative steps. We are not at the gigafactory scale in fuel cells, and we need to get there if we are to see the cost benefit, but the UK is well placed in having a bedrock to build on, if that is what we choose to do.

I reinforce Pam's point that, whether it is fuel cells or batteries, we need this commitment to create market and to scale up if these technologies are to be taken forward. We also need to remember that it is a global market. While the UK market matters, from a UK plc perspective the ability of companies in the UK to access global markets is very important. There is a lot of excitement in Asia, North America and elsewhere in Europe that we can take advantage of.

In addition to lithium ion batteries, which is clearly an extremely important area, I would highlight the potential for flow batteries as we move towards longer-term energy storage for stationary applications in the four, 12 or 24-hour range. The UK also has some inventive technology there, which is very similar to fuel cells in many respects.

Lord Krebs: Lord Kakkar asked about the sustainability of using the current materials. We will come back to this later, but could you just answer very briefly?

Professor Pam Thomas: I am happy to defer to Professor Pasta on this.

Professor Mauro Pasta: In terms of the availability of raw materials for car lithium ion battery manufacturing, yes, we have enough. There are supply chain and geopolitical issues that we need to consider, as demand will increase in the future. Many have referred to lithium as the oil of the 21st century, so you can draw a parallel in that sense. There are environmental concerns associated in particular with the mining industry. Recyclability will become more and more relevant and important, particularly as the penetration of electric vehicles in the market increases.

The Chair: I thought the world's supply of lithium in the soil was plentiful and that it was just a matter of using sodium chloride to extract it. Am I wrong?

Professor Mauro Pasta: There is plenty of lithium, actually. It is a matter of cost and how easy it is to extract. More or less 50% of the total amount of lithium is in the lithium triangle in South America between Bolivia, Argentina and Chile[2]. We have started observing some environmental concerns about its extraction. In Chile, for example, lithium extraction requires quite a lot of fresh water. It is a simple process. There are local concerns associated with that request for water. In terms of raw material availability in the earth's crust, there is plenty of lithium.

Q8 **Baroness Manningham-Buller:** I am getting a mixed picture of where we stand. If we are going to make the step change to the next generation of technologies to which Professor Thomas referred, what research are we doing? How does the UK rate against other countries in the research into these areas, in British universities or elsewhere?

Professor Mauro Pasta: The strength of the UK is in its fundamental science. I believe that it is second to none. In that sense, particularly

[2] The following link was provided after the evidence session: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-lithium.pdf [Accessed on 20 March 2021]

with the Faraday Institution, which you can consider the research branch of the Faraday Battery Challenge, we are making a lot of progress and leading in a lot of battery research and development sectors. In that sense, I would not be worried.

We might discuss for a second our past weaknesses in the translation of that fundamental research. For example, we heavily contributed to the invention of lithium ion batteries 40 years ago. We did not really capture the value. The Faraday Battery Challenge and Faraday Institution are making a substantial effort to address these issues and foster collaboration within academia and with industry. We are in a good position.

Baroness Manningham-Buller: It is very encouraging that you believe we will make the maximum of these discoveries. Do you agree, Professor Brandon?

Professor Nigel Brandon: It depends. It is a bit different in the fuel cell space. The battery space has, quite rightly, received a lot of attention. The Faraday initiative is clear evidence of that, and I certainly welcome it. The website of Research Councils, the primary vehicle for funding academic work in the UK, says that fuel cell technology is not currently a high priority for government or industry, which is a bit of a damning reflection of the funding landscape at the moment in the fuel cell space. There is an opportunity to do more.

If I look back 20 years, there was a much stronger level of investment in this area. A number of the companies that collectively are currently worth well over £6 billion came out of academic research and spun out from universities 20 years ago. It takes that long for innovation to reach true market scale in these materials-rich areas.

The UK's science base is very strong in electrochemical technologies and electrochemistry, which underpin fuel cells and batteries, so it is a great place to leverage. We have got a lot better at translating that. These are also multidisciplinary topic areas. It is not about an area of science, but about a collection of scientific disciplines working together to create and support technologies. We are good at talking to each other across disciplines in the UK, but we are a bit subcritical in capacity, particularly in the fuel cell area at the moment, because the funding landscape has not been supportive of fuel cells for a number of years now.

Baroness Manningham-Buller: What does the UK need to do to improve the situation and get to this position where, as Lord Kakkar put it, we can leapfrog? When we do a report, as you will understand, we are always thinking about what our recommendations might be. Professor Thomas, it would be helpful for the committee to hear how the UK can make the step change to the next generation, skipping this one, that you said was needed to get where we need to be in the next 15 years or more.

Professor Pam Thomas: I partly answered that in my previous comment, which was about ensuring that there is a long-term vision and plan for research, development and innovation in this country to get to that point. It should be mission-inspired research, somewhat like the Faraday Battery Challenge. We laid the foundations for that being a successful way of doing things in the UK, where you bring the nationwide academic community together on large projects, which are shaped by the industries that will take them up and have clear outcomes and goals. Here, we have a goal that is set for us in a sense in wanting to get to net zero by 2050. We need to co-ordinate our research and our work with the industrial beneficiaries and exploiters to get to that point. That vision is sometimes sadly lacking in the UK's funding for science.

Baroness Manningham-Buller: You are saying that you can have the vision and the plan, but you need more money.

Professor Pam Thomas: I would not say it as directly as that. We need the commitment, which is to say that this is not a short-term thing. Once we have done three years, we have not finished. We need to do the five years and the 10 years. We need to keep going on the path.

The Chair: Professor Thomas and Professor Brandon, we do not have time today, but it would be very helpful if you could send us a short paper, individually or together, that says where we are, where we should be and what there is in between that requires to be done by research funding, government or whatever to get there. What will the consequences be if we do not do that?

Q9 **Lord Mitchell:** If I am reading this correctly, on the research side we are probably doing okay, we are up there with the best, but we need more funding and more direction. That is the message I am getting. I am always concerned about the developments and how we will benefit as a nation. I am sure that we have all seen too many examples of great ideas and developments which other countries benefit from. You think about integrated circuits and the mass production plants in South Korea, Taiwan and elsewhere. I wonder what we need to do to make sure that GB plc is at the forefront when it comes to manufacturing. Do we have the skills? Do we have the direction?

Amer Gaffar: I believe not, but we can get there. It is all about that long-term plan that Professor Thomas mentioned. We need a long-term plan for skills. We have been talking about markets here. Batteries are clearly more mature than fuel cells, but fuel cells will become more mature. We are heading towards net zero, so our plan should be working with the large industrial clusters that are looking to achieve net zero at scale. It is about a co-ordinated response, working alongside that energy transition response, to ask, "What will get us there?" Will it be batteries? Will it be fuel cells? It will be an amalgamation of everything. As academic institutions, how do we combine our activity in the UK or in the north-west?

There should be more of a co-ordinated response to ask, "Are we teaching the courses that allow us to get there?" We are not just talking about high-level skills. We should be considering level 1 and 2 all way through to level 8. We should be considering the children who are in school today and teaching them about hydrogen, fuel cells and batteries.

If you are training to be an electrical engineer today, is that enough? That co-ordination is key and it is probably one of our strongest assets. As my colleagues have proved, the technology exists, but do we have the people and are we making the right people, all the way from school level up to PhD and postgrad level?

Professor Pam Thomas: I entirely agree. We need investment in skills from the very top academic level, the PhD students, and the pipeline to become the professional scientists and engineers of the future. At the other end of the scale, we need to start with our schoolchildren, and certainly our apprentices as they go into industry. A road map is being developed with the skills that are required. The Automotive Council is working with Warwick Manufacturing Group, WMG, to provide a skills framework for the nation, through from apprentice stage, 16 and 17 year-olds in technical colleges, right into the professional scientist PhD.

There is also work going on with our emergency services—with the police, the fire service and so on—to consider how we tackle fires and emergencies based on battery-powered vehicles instead of the internal combustion engine. All these things in society have to be modified to take into account the fact that the underlying technology is different.

Q10 **Lord Sarfraz:** I declare an interest in venture capital, as set out in the register.

Consumers are still hesitant when buying an electric car. They worry about the driving range, the cost, the charging infrastructure et cetera. What are the main challenges that we need to overcome in battery technology, so that everyone can benefit from an electric car and it is just a no-brainer to go out there and buy one?

Professor Mauro Pasta: Let me go in order. First, there is manufacturing. As Professor Thomas mentioned, if we want to translate to a full EV by 2050, we will need over seven gigafactories[3]. We have zero now and it takes five to seven years to build one, so we need to make batteries. Secondly, we need to reduce cost. As we mentioned, economies of scale have done that job in a way. We are now approaching the physical chemical limit. We need to look at technologies beyond lithium ion batteries in order to further reduce the cost.

In terms of performance, we talked about manufacturing, we talked about cost. Range is associated with introducing more energy-dense technology. As you increase energy density, you decrease cost and increase range. Charging times, with the current technology, are a bit of a problem. It takes about an hour and a half to charge an EV right now with a supercharger. If we want to take the next step, we need to change technology. The only one on the landscape right now that will allow us to do that substantially is probably solid state. We need to focus our

[3] The following link was provided after the evidence session: https://faraday.ac.uk/wp-content/uploads/2020/03/2040_Gigafactory_Report_FINAL.pdf [Accessed on 20 March 2021]

attention on these leap-forward technologies if we want to get there and tackle all these issues together.

Professor Nigel Brandon: It is a little different on the fuel cell side. The question is angled at a transport application. That is fine, and I will answer in that context, but there are other applications for fuel cell technology that are not transport-related.

In terms of transport applications, the biggest barrier is the refuelling infrastructure—in other words, the availability of your hydrogen fuel to customers who will buy those vehicles. We have a hydrogen fuel Toyota Mirai at the university. It is a nice car. It does 300 miles on a tank of hydrogen. You can refuel it in three minutes, but there are only a handful of refuelling stations around London, so it is inconvenient. It is quite expensive; it is £50,000. So there are cost and refuelling issues in transport.

Hydrogen buses are a different type of issue, and the refuelling infrastructure is not so much the issue there. They go from a central point, so the issue is the cost of that technology and how we get it down. At the moment, they are sort of boutique and made in low volume, and are therefore expensive products. We need to drive up that volume and those manufacturing scales.

As I say, in 2019 45,000 consumers in Japan put a fuel cell into their home to produce heat and power for the home. If you are going to put fuel cell products into people's homes, that is great, but they need to compete with other low-carbon heating technologies, which means getting the price down, which means getting the cost down. There is a range of barriers. Cost is a common barrier, however, regardless of the application. In some of the transport applications, there are also refuelling barriers on the fuel cell side.

Q11 **Baroness Rock:** I will come back to the battery technology, if I may. Professor Pasta, you talked about cost, energy density and charging times. I wondered if we could drill down on the projected trends and particularly the timescales, given that Professor Thomas is very clear that it takes a long time to bring these things to fruition. Are we, as UK plc, leading in research and innovation in any of these specific areas?

Professor Mauro Pasta: I might be a little biased, because I am leading the project on solid-state batteries. In the next 20 years, if we want to be ambitious and look forward, probably the only technology that tackles the three key issues that I mentioned—energy density, charging time and safety—is solid state at the moment. The big question mark about solid state is cost. We are building gigafactories all around the world, and if solid-state technology is not compatible with them there will be a problem.

It is difficult for me to make a prediction, because we still have some fundamental scientific questions to answer and tackle right now. That is what we are working on. We need to wait for a couple of years to understand whether the issues associated with scale are solvable and addressable, or whether we need to approach the manufacturing of solid state in a completely different way.

Professor Pam Thomas: Mauro's modesty is nice to behold. He is declaring a conflict of interest, in the sense that this is his science. It is truly excellent science and is being led by a world-leading team, so that is good for the UK. The targets that we are working to within the Faraday Battery Challenge as a whole, of which the Faraday Institution is the research organisation, are to get to one-third of the cost, two times the energy density, four times the power density and two times the lifetime. That is what we are working to with our improved battery, which may well be based on solid-state technology.

In a way, the fact that we do not have large production of the current battery technology is a good thing for the UK, in the sense that we need to leapfrog it. For our gigafactories, we can invest in the new emerging technology that typically takes 10 years to come from the chemistry lab to manufacturing. Rather than look at this as a sadness that we missed out on the lithium technology that was indeed invented in the UK, we should be looking forward to the fact that we can leapfrog the competition by concentrating on emerging technologies of the sort that Professor Pasta is currently working on.

The Chair: You keep talking about leapfrogging. I am sure the Germans, the Chinese and the United States are not standing still. They are also clever people. How are we going to leapfrog over everybody?

Professor Pam Thomas: I will continue on that, since I am the one who has used the word "leapfrog". That is entirely right. We are still in a massive global race against countries that are investing far more in this technology than we are. Even if we just look across to Germany, the equivalent of its Faraday Battery Challenge project has been at the €2 billion scale, compared with £300 million, which I am not denying is a lot of money, especially in the current climate. We are working at a lower scale than much of the competition and we need to keep an eye out for that. That is why I said that we need to be really committed to doing this if we are to succeed in a global race.

Q12 **Baroness Sheehan:** I would like to delve a little further into the potential for fuel cells in powering surface transport, including heavy goods and trains. To get some more information on that would be very good. In your answer, could you also address the challenges facing technological innovations and deployment in heavy transport, not least the refuelling infrastructure that Professor Brandon touched on?

Amer Gaffar: Nigel will provide a much more varied response with regard to the technology itself. From our perspective, when we are supporting businesses or organisations in our city region to make investment decisions, the total cost of ownership question comes up. We then introduce other aspects, such as future electricity prices, clean air zones or the likelihood of taxation on electric vehicles or hydrogen fuel in the future. All of a sudden, the investment decisions that they need to make, which need to stick around for 10 years because that is when they replace their fleet of transport, buses or heavy goods vehicles, start to make a lot more sense to them.

From their perspective, they think that they can make an impact, especially with fuel cells in heavy goods vehicles, but I come back to what Nigel said earlier: the lack of infrastructure is informing decisions. The lack of hydrogen refuelling infrastructure is informing many decisions for multiple fleet operators across the region, because we do not have any. There is a plan to have it, and I think the investment decisions will change accordingly.

Professor Nigel Brandon: Yes, you are right. When it comes to land transport, the sweet spots for hydrogen fuel cells are the heavier-duty, longer-range vehicles and trains, which are looking particularly interesting for electrifying relatively low-use suburban lines, where you can replace diesel with hydrogen fuel cell electric trains. As has been pointed out, you have to address the refuelling issue. For a bus fleet or a train operator, this is actually a much easier problem, because the buses run from one place and the trains largely come back to the same place on a suburban line, so that helps mitigate that.

None the less, we need to drive down the cost of hydrogen refuelling infrastructure. It is not just about the fuel cell, which is the power train, but about all the other components around it—the hydrogen storage tanks, the sensors, the blowers—which are needed to put these things into service. All those costs need to come down. There is UK industrial representation right across that supply chain. We are involved in fuel cell development but also in vehicles. We have a company in London called Arcola Energy doing bus and train integration, for example, as well as companies in other aspects of electrification, on the power electronics side and so on, that are all relevant to providing that supply chain.

In terms of the barriers, this is about engineering and manufacturing innovation to drive down cost. It is largely cost, plus the commitment to a hydrogen refuelling infrastructure. As ever with these things, it is a more difficult proposition for the early adopters, because you have this circular debate between the volume of hydrogen you will sell and people wanting the hydrogen, because it is not available. Risk mitigation for early adopters matters. That is where local, regional and national support can clearly play an important role.

You need to co-create and co-develop the hydrogen supply side for the fuel, if it is a hydrogen fuel cell, and the demand side. In other words, you need to build the demand, the supply chain and the infrastructure that joins it together at the same time, on the hydrogen side of transport. If it is a stationary application, for example producing heat and power for a distributed generation type technology, it can run on natural gas today. That gives you high-efficiency energy conversion of natural gas. It could switch to hydrogen tomorrow if we were able to put hydrogen down our natural gas lines, which is the topic of another conversation about how we decarbonise the heat sector, for example.

Baroness Sheehan: Professor Brandon, you have mentioned a couple of times that the cost of deploying fuel cell technology is bound up in the storage of the hydrogen. Can you say a little more about why that is so expensive? Could you touch on the safety aspect of hydrogen fuel cells?

Professor Nigel Brandon: Those two things are coupled together, in that you would put technology out there only where it was safe. Hydrogen for vehicle applications is stored at either 700 bar or 350 bar pressure. These are high-pressure tanks. Therefore, they need to be engineered to be safe, to be strong and to withstand impact—people firing guns at them and all sorts of things, depending on where they are in the world. At the moment, these are almost aerospace-grade technology tanks, made with aerospace-type composite materials and Kevlar. Those tanks are essentially handmade in low volumes, so at the moment they are expensive.

The automotive companies are confident that, by increasing volumes and therefore going to different manufacturing processes for the same materials, you would significantly drive down cost. There has been some nice work at the University of Ulster, for example, looking at how you make a much safer tank at lower cost. These two things are coupled. We must ensure that we address the safety issues and hit the cost targets.

Q13 **Baroness Walmsley:** We also have to produce the hydrogen in a zero-carbon way, which is a different conversation. What competing technologies are there for decarbonising this heavy surface transport sector? What are the advantages and disadvantages of batteries and fuel cells compared to these other possible technologies?

Professor Nigel Brandon: I will kick off on the fuel cell perspective and then ask my colleagues to speak to the battery perspective. With longer-range vehicles it is all about the energy density of the fuel. I do not think that fuel cell electric is competing with battery electric at this point. Hydrogen fuel cell electric is competing with synthetic fuel combustion. It is more likely that you are competing with a so-called e-fuel, or a fuel made from combining hydrogen with CO_2, producing some form of synthetic liquid fuel and then burning that in an engine, than with a pure battery solution. My colleagues may disagree.

With longer-range vehicles, you are also competing with ammonia as a carrier, which could be an ammonia fuel cell or, for ships, ammonia for stroke engines. You are absolutely right: it is all about the carbon intensity of the fuel combined with the efficiency of the energy conversion process. Fuel cells give you very efficient energy conversion. The carbon intensity depends on the fuel. They will always be more efficient than an internal combustion engine, but there are other factors to bear in mind, such as cost and weight.

Professor Mauro Pasta: I am not an expert in this area, but I can say, and Nigel touched on it, that the current energy density of lithium ion batteries is not at par with fuel cells. In that sense, I believe that hydrogen will play a more substantial role in that area.

Professor Pam Thomas: I do not disagree. I am completely with my colleagues on this one. In all these applications, it is horses for courses. You need to choose the right technology for the right application. There is no one-stop shop where battery technology will fix everything. It is right that we need to look across the whole landscape at what the right things are for the right applications.

Baroness Walmsley: I have a quick technical problem about refuelling in general. Is there any reason why the current battery charging infrastructure is mostly slow chargers? Why are there very few really rapid chargers? Is it anything to do with that infrastructure that makes it difficult?

The Chair: Give us a quick answer, please. I imagine it is cost and infrastructure.

Baroness Walmsley: Is that all it is, or is it technical?

Amer Gaffar: I would refer this to Professor Pasta. As a person who owns an electric vehicle, I can tell you that there are not many rapid chargers around. When they are around, people tend to plug their cars in and leave them there for quite a while. That is the real-world problem, from my perspective.

The Chair: It is an infrastructure issue. Is that right, Professor Pasta?

Professor Mauro Pasta: I will keep it simple: yes.

Q14 **Baroness Warwick of Undercliffe:** Good morning. I had better declare my interests. I am the chair of the National Housing Federation, the chair of the Property Ombudsman, and the deputy chair of the board of Nottingham Trent University.

My interest here, unsurprisingly therefore, is more in buildings and homes, but it was quite interesting that we focused almost entirely on transport in this conversation. It was Professor Brandon who talked about other sectors which these might be relevant to, not just transport. Could you explore that and tell us where battery and fuel cell technologies are not currently used but could contribute to decarbonisation? I would appreciate it if you could say something about homes and heating, and perhaps add something in a practical sense about retrofit. If one considers that 80% of all homes that we will have in 2050 are already built, we have quite a challenge.

Professor Nigel Brandon: There is potentially quite a long answer to your question, so I will try to pick out one or two bits. In terms of where fuel cell technology plays a role in this regard, you are right: we have focused a lot on transport, but there is a lot more to the decarbonisation agenda than transport. Heat, which is about 40% of our carbon emissions in the UK, is a substantive challenge.

I come back to the fact that you decarbonise through the choice of fuel. In other words, we cannot continue to supply natural gas to heat our homes. We have to do it differently. Either we move to electricity and use heat pumps, or we move to hydrogen and convert that into heat. If we do, it makes a lot of sense to put that hydrogen into a fuel cell in the home. That is what the Japanese are doing, with 45,000 units purchased in 2019 to heat and power homes.

If you put the low-carbon fuel into the home and convert it in the fuel cell, both to power the majority of the home and at the same time to capture the heat, that gives you a better use of that fuel to produce heat and power. It allows you to make the electricity in the home. If, for example, you combine that with electric vehicle charging, you do not have to invest as much in the low-voltage distribution network to put power in for electric vehicle charging. You can generate it locally within the home.

These so-called combined heat and power systems are of potential interest. They have the advantage for the consumer that you do not need to retrofit all your radiators. They just work like a boiler as far as the consumer is concerned, whereas with heat pumps you need to put in a very different radiator system. They are a much harder retrofit, particularly into a lot of the UK building stock. There are some potential advantages there, which brings in a broader debate about the energy carrier itself and how you should best use hydrogen. If you are going to use hydrogen, fuel cells are a jolly good way of turning that into something like electricity in a very, very efficient way. Bear in mind that a fuel cell in a home is about as efficient as a 100 megawatt combined cycle gas turbine power plant, so it is a very efficient way of making electricity.

In terms of the broader system and the roles of the batteries in general, it is all about balancing supply and demand and helping the system to function. We will need a range of storage technologies that balance it second by second, which may not be a lithium ion battery; minute by minute and hour by hour, which probably is a lithium ion battery; and then potentially for hours or even days. If we are going to 10 or 12 hours, we might consider flow batteries. We have not spoken a lot about that, but it is an alternative battery technology.

If we go into days and weeks—we may need to balance offshore wind in winter or a low period of wind for several weeks—we may want to store our strategic reserves as hydrogen in underground caverns, which would give us enough energy to balance out a two or three-week shortfall in wind supply, for example. I will stop there, but we could spend the whole time just on this.

The Chair: I wish we had that time. It is interesting.

Professor Mauro Pasta: We agree with what Professor Brandon just said. I want to reiterate the importance of grid-scale energy storage moving forward. It could be even more impactful in terms of gigawatt hour and installed capacity than EVs. As we mentioned, these technologies are both energy storage technologies and they are not really generation technologies, although the fuel cell may be a bit closer. Renewable energy is very intermittent in nature: unfortunately, the sun does not always shine and the wind does not always blow. As we increase the percentage of renewable energy, as we all want to do, we need energy storage technology that will allow us to smooth that power output.

Professor Brandon mentioned the different timescales. You go from milliseconds to seconds for frequency regulation. There are technologies such as supercapacitors, which we have not talked about. Lithium ion batteries are in the minutes to hours. Moving forward, there are redox-flow batteries in hydrogen.

I would like to introduce a consideration, though. As the penetration of electric vehicles increases, we will have more and more batteries with a potential second life if we want to decrease and depreciate these barriers even more moving forward. That will definitely play a role in this area. Quantifying what the role will be in future is quite difficult, because it is very difficult to predict the lifetime of the usage of a car, but they will play a substantial role.

Q15 **Lord Winston:** Coming back to what you and Professor Brandon said, can we explore this business of storage with regard to the National Grid? I remember when we first heard how wasteful the energy storage was at the National Grid—for example, how medieval it seemed that we pump water up hills to store energy. I wondered where you thought batteries might play a much bigger role in the storage of energy, because that is one problem that would be really worth trying to sort out.

Professor Nigel Brandon: As Mauro has just said, this is all about timeframes. Different technologies will have different strengths and weaknesses, and different timeframes. If you want to balance frequency response on the grid, making certain that the sine waves are all properly balanced and everything is in phase, you need to be able to move energy around on a millisecond or second basis. You need to do that thousands and thousands of times. Supercapacitors are very good at that. That is the technology that we will probably use.

If you want to balance energy over half an hour, one hour or two hours because you have a particular peak and you want to release the load on the substations or something like that, given the price point where lithium ion is it makes a huge amount of sense to use that. The duty cycle there is different from the duty cycle in a car, so we will need to think about how we tailor the batteries for that application, but the principles are not dissimilar. You would have some bespoke chemistry that was attuned for that particular type of application, because the charge and discharge rates will probably not be the same as you might experience in a car. The number of cycles is probably different, so you tune it to that.

In California, where they already have very high penetrations of solar, they are finding that they need about 10 hours of storage to balance the Californian energy grid. That is looking like the sweet spot for California, with very high solar penetration. At 10 hours of storage, lithium ion starts to get quite an expensive proposition, because you need 10 times as many batteries as you need for one hour.

This is where technologies that decouple power and energy, such as flow batteries, compressed air energy storage and liquid air energy storage come in. There is a raft of options enabling you to have a much lower cost of energy storage. I declare an interest: we have a company in this space. We believe we can get to less than £50 per kilowatt hour energy storage out for 24 hours, which is a very cost-competitive storage option.

In the UK electricity context, given that we will go for large amounts of offshore wind, we will want to balance inter-seasonally and provide a strategic reserve. If we have no wind blowing for two weeks in the winter, that is about 20 terawatt hours of energy storage. If you are familiar with the Dinorwig pumped hydro, known as Electric Mountain in Wales, that is about 2,000 Dinorwigs. You cannot practically store that much energy with pumped hydro. Pumped hydro is a good technology: it is low cost and is about 70% round-trip efficiency. But this is not all about efficiency. It is really about the cost of providing that service. Efficiency matters, but it is not the only thing that matters.

You have a range of storage options. If you look out to the future, all the forecasts are that we will need more of each of those, so this is potentially an enormous market and an enormous need. The UK is well placed and has companies active in the space that I have just described.

Professor Mauro Pasta: I fully agree with Professor Brandon. It is a very good summary. We need different technologies because we need different timescales for storage.

Professor Pam Thomas: I was just about to repeat "horses for courses". As Nigel has very eloquently said, we need different storage for different applications. I absolutely agree.

Amer Gaffar: I fully agree with what everyone else is saying. It is correct. That is what we are finding in our university and the region.

Q16 **Lord Krebs:** I would like to return to the question of environmental impact, which we have touched on before in talking about mining for lithium, but I wanted to look at it slightly more in the round. I wonder if our experts could comment on the life-cycle environmental impacts of batteries and fuel cells compared with conventional energy sources. Life cycle would include both the direct environmental impacts of mining, pollution and so on, and the energy costs of transport and production.

Professor Nigel Brandon: I will restrict my comments to fuel cells, because it is the subject I am most familiar with. In this context, I have been involved in work looking at the life-cycle analysis of both low-temperature and high-temperature fuel cells. There are different types of fuel cell technology, which we have not gone into here, but, as with energy storage, they play to different strengths and weaknesses in their application area, the low-temperature type being most commonly found in transport applications and the higher-temperature type in stationary.

When you do the life-cycle assessment, you find that it is dominated by the use phase. Fuel cells are an energy efficiency technology; they allow you to use the fuel more efficiently. That saving impact gives them a substantive round-trip efficiency and life-cycle gain. The energy penalty is the amount of time you need to use them to pay for the burden of manufacturing them. I cannot remember the number off the top of my head, but is a very short time. It is weeks rather than years, so these technologies are well served environmentally.

That is not to say that there are not environmental footprints. In particular, the low-temperature technology uses a fluorinated membrane, and you need to take care in the manufacturing of that membrane and its recycling. In other respects, the footprints are low. The emissions of NOx, SOx and particulates, which are essentially zero, and energy intensity in the use phase, are very low.

Professor Pam Thomas: To come back to specific applications, because one has to consider these things piece by piece, let us take the life cycle of carbon emissions for an electric vehicle. The carbon footprint in an electric vehicle depends on vehicle production, battery manufacturing, electricity production, EV use and end-of-life recycling. One has to look at the various phases of the carbon footprint of an electric vehicle.

We want to make the manufacturing as carbon-free as possible. In that, one has to consider how to set up a battery manufacturing factory, for example. One might look in the UK at Britishvolt. Positioning that gigafactory up in the north-east means that it is very well placed to use offshore wind energy as its primary source of electricity for the manufacturing of the batteries. This goes right back to the beginning in asking, "How do we actually manufacture the components that go into the vehicle?"

We also need to consider the end of the life cycle, where one wants to recycle the batteries and possibly give them a second lifetime of use. BMW has a very large second-life battery farm as part of its vehicle manufacturing production in Germany. It is taking its own batteries and using them as recycled batteries for its grid.

We also need to consider the behaviour of the consumer in bringing the battery forward for recycling at end of life. The proper time to do that is after about 70% or 80% usage, whereas the behaviour of the consumer is normally to run the battery down to dead before they look to recycle it. That is losing out on some of the benefit one can have from the second life of a recycled battery.

There are lots of components to this: how you manufacture, how you recycle and how the consumer behaves. We need to consider this in our policy work going forward.

Amer Gaffar: From a fuel cell perspective, some of our academics are saying that platinum can be recycled. I am sure Professor Brandon can point that out. If you use platinum in a fuel cell, it is not that you will not be able to use that again. It can be recycled.

Professor Mauro Pasta: I would like to highlight the importance of recycling moving forward and how challenging that is in the lithium ion battery space. To put it in context, lead acid batteries that have been around for 150 years are very close to 100% recycling. There was a study a couple of years ago from Australia that said that only 2% of over

3,000 tons of lithium was actually recycled.[4] That is a problem moving forward.

This problem will become more and more pressing very, very soon. Most of the EVs today have yet to reach the end of their life cycle, so the problem will start appearing soon. There are some fundamental technical constraints, mostly associated with the disassembly of lithium ion batteries. It is quite complex compared to lead acid, because some of the active material components degrade over time. They cannot simply be replaced and used in a novel technology. Manufacturers are also understandably secretive about the composition of their components, which makes it quite difficult to recycle.

To put it into context, we recycle batteries right now through what is called a pyrometallurgical technique. More practically, we burn everything and we try to recycle as much as we can. As you can imagine, this is not the most efficient way of doing it. The Faraday Institution has a project, led by the University of Birmingham, that is fully dedicated to recyclability, and we are making progress in that aspect.

Q17 **Baroness Brown of Cambridge:** I find the discussion about recycling quite frustrating, given that we extract metals from very, very lean ores with sometimes very complex compositions. It seems to me that the electrodes of a battery are the equivalent of a very rich ore. Why is this such an enormous challenge compared to the challenges we already take on?

Professor Mauro Pasta: It is a challenge, because it has to be recycled efficiently. It is possible, but it is very complex and, at this point, not economically viable. It is easier to mine new lithium, cobalt and nickel than to recycle. We need to change that. We are talking about the raw materials, but even disassembly is very complicated for a lithium ion battery compared to lead acid, as I mentioned earlier. A project led by the University of Birmingham is looking at automating these processes as much as possible, because separating the active components will make this recycling easier and easier moving forward.

There are technical challenges, but mostly economic challenges. It is not viable right now without the help of policymakers. It will take quite a while for recycling to be fully economically viable, so we also need some help from policymakers on that side.

Baroness Brown of Cambridge: Okay, so it is not really that it is technically difficult. What kind of recovery can we expect? Are we talking about 70% of some of these key materials or up to 98%?

Professor Mauro Pasta: Professor Thomas may be more aware of what is going on in the University of Birmingham. I would not want to give an inaccurate number.

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[4] The following link was provided after the evidence session: https://publications.csiro.au/rpr/download?pid=csiro:EP181926&dsid=DS1 [Accessed on 20 March 2021]

Professor Pam Thomas: Apologies, but I cannot give you a number for that. In answer to your question about why it is so difficult, the batteries in their packs within an electric vehicle have quite often been subject to a lot of abuse before they reach the recycling point. Therefore, it becomes a matter of trying to recover precious minerals from something that is in quite a bad state by that time.

At the moment, vehicle manufacturers are simply putting the battery packs into a large shredder, generating piles of black powder and then doing the necessary chemistry to recover the previous metals from the black gunk they have in front of them. It is not very sophisticated. The project that Mauro was referring to, run from the University of Birmingham, is looking at making that much more sophisticated, in particular to prevent wastage on the production line. That becomes a cost saving to the manufacturer and is much more likely to be adopted by them.

Baroness Brown of Cambridge: That suggests that batteries are not being designed with recycling in mind. If you were designing them with recycling in mind, you would be making them much easier to take apart.

Professor Pam Thomas: Yes, that is absolutely right. That is in the next phase of thinking of automotive manufacturers across Europe and the world.

Baroness Brown of Cambridge: Are you doing any work on that in the Faraday Institution?

Professor Pam Thomas: Yes. Part of the recycling project led by the University of Birmingham is looking at how to design in better recycling prospects at end of life.

Baroness Brown of Cambridge: Are second-life applications being taken into account in the design of batteries?

Professor Pam Thomas: That is certainly being done. I mentioned the battery farm that is being used by BMW at the moment to provide energy to its manufacturing plants. That will only become more important. On the European continent, it is particularly being driven by regulation, in that life-cycle consideration and end-of-life use must be built into every piece of technology that is developed.

Baroness Brown of Cambridge: I would now like to ask a completely different question of Professor Pasta. You are talking about the step change that we need in solid-state batteries, which we hope might come in the 2030s at the earliest. By then, we will have put in an enormous amount of charging infrastructure. Will all of this be compatible with solid-state batteries?

Professor Mauro Pasta: Yes.

Baroness Brown of Cambridge: There is no difference. We can fast charge them in exactly the same way; we can slow charge them. I imagine that is quite straightforward, but is all the fast charging going to be compatible with them?

Professor Mauro Pasta: Yes, I believe so.

Q18 **The Chair:** I am interested in asking this question. My physics, from a long, long time ago, says that in a battery there is an anode, a cathode and chemicals. I might be wrong; that might be simplistic.

Professor Mauro Pasta: It is a good summary.

The Chair: If we are looking at the casing that would enclose all that and the chemicals that would make energy denser, why is it not possible to design a battery that is completely different from the current concept, and therefore make the parts recoverable later?

Professor Mauro Pasta: It is a good question. The real challenge is that, if you want to make this battery energy-dense, you want to pack everything as closely as possible. You do not want to have any empty space or any voids. This assembly, if you are familiar with how an EV battery pack is composed, is made of thousands of single cells, about 10,000 on average. Separating the single cells is easy. It is when you are trying to recycle what is inside a single cell that it gets a little more complicated.

In addition to what you mentioned earlier, you have a cathode, an anode, a separator, which is a polymeric membrane that prevents them short-circuiting, and a liquid electrolyte in between. We can separate the anode; we can separate the cathode. We are also getting better at separating the three components in the battery. It is reusing the active material that is challenging. Right now, it is easier to completely dissolve and destroy them, separate them and remake the actual cathode materials. One avenue of research is to separate the active material itself, try to reformulate it and use it in a battery moving forward, but, as mentioned, there are challenges associated with material degradation that are currently impeding us in achieving that goal efficiently.

The Chair: To summarise the session, I get the feeling that, while we have world-leading scientists in both battery and fuel cell technology development, we are nowhere near taking this science to develop technologies at such a scale that we, as a country, could become the world centre in any particular aspect. Am I completely wrong?

Professor Nigel Brandon: We have some great science, some great companies and some great technology. In the fuel cell area, we have international players such as Bosch investing in British technology and helping us to build manufacturing facilities here. To pick up on Pam’s point, we need to bring the academic strengths together with those industrial strengths; we need to work together to stay ahead of the competition, which is significant; and we need to move quickly to scale. We have the building blocks of that, both industrially and academically, but we need to work together to realise it. There is a prize to be won here and we are in a good place to win it.

The Chair: What does that working together look like?

Professor Nigel Brandon: In research and innovation terms, what Faraday has done is a really good model for bringing academia and industry together. There are lessons to be learned from what we have done so far with Faraday, which we might fine tune. The principles of an ambitious, challenge-led programme that looks not only at the science but at the manufacturing and deployment, which harnesses the strengths of both those communities and works together towards a common set of objectives, would be fantastic.

Q19 **Baroness Walmsley:** That answer leads very nicely into what I was going to ask about. The only person who has mentioned engineers is Professor Thomas. In making the step change that we need to make, are we not forgetting engineering, energy-efficient manufacturing and the development of the power train? How much of the improvement that we need to make will have to come from those things?

Professor Pam Thomas: Engineering is crucial in this. The Faraday Institution is joined to an engineering provision through the other parts of its challenge. We are based on the electrochemical storage side and we tend to have more pure scientists—chemistry, physics and so on—than engineering. My next stage in the evolution of the Faraday Institution is to connect that much more strongly to our academic engineers, as well as our industrial engineers.

For the implementation of all this fantastic pure science in the field, we need our engineers entirely engaged upon this. They are also getting engaged through the Faraday Battery Challenge. What we are doing is bigger than just the Faraday Institution, but we need more of that. I am clear that the engineering skills and provision in the UK is vital to achieving this net zero ambition.

The Chair: I have just about kept to time. Mr Gaffar, Professor Brandon, Professor Pasta and Professor Thomas, thank you very much indeed. We thoroughly benefited from your wisdom today. If, on reflection, you want to write to us on any of the questions—I posed one to you, Professor Thomas and Professor Brandon—it would help our deliberations and our report. Anything you send in that enlarges on the information you have given us is most welcome. We appreciate all of you making time today to help us. Thank you very much indeed. Goodbye and good luck.