



Select Committee on Science and Technology

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

Tuesday 16 March 2021

11 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 Sheehan; Baroness Walmsley; Baroness Warwick of Undercliffe; Lord Winston.

Evidence Session No. 3

Virtual Proceeding

Questions 32 – 48

Witnesses

Professor Andrea Russell, Professor of Physical Electrochemistry, University of Southampton; Professor Anthony Kucernak, Professor of Physical Chemistry, Faculty of Natural Sciences, Department of Chemistry, Imperial College London; Professor John Irvine, Professor, School of Chemistry, University of St Andrews.

USE OF THE TRANSCRIPT

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

Examination of Witnesses

Professor Andrea Russell, Professor Anthony Kucernak, and Professor John Irvine.

The Chair: I welcome our next witnesses: Professor Russell; Professor Kucernak—I hope I have pronounced that correctly; and Professor Irvine. Thank you very much for joining us today. We appreciate it very much, as you are giving up a lot of time to help us with our inquiry today. Before you answer the first question, can you please say for the record who you are and any other designations that you have.

Q32 **Lord Mitchell:** I have no interests to declare. What are the main types of fuel cells and how do they work? What type of fuels are most commonly used in fuel cells?

Professor Andrea Russell: I am from the University of Southampton. I am an electrochemist and I specialise in the study of the electrocatalysts that go into fuel cells. I have no interests to declare.

We define the types of fuel cells mostly in terms of the temperature of operation: there are solid oxide fuel cells, which work at a higher temperature, and polymer electrolyte fuel cells, which work at more standard temperatures. That is the main difference.

The difference between batteries and fuel cells is that batteries store energy, as you heard earlier today or maybe last week, and fuel cells produce energy. On the types of fuel, hydrogen is probably the most desirable, but we can also use ammonia, methanol or biogas. That is a brief answer to your question. I can hand over to my two colleagues to add more information.

Professor Anthony Kucernak: Hello everyone, and thank you for the opportunity to speak today. I am professor of chemical physics in the Department of Chemistry at Imperial College. I am also the lead on polymer electrolyte fuel cells and electrolyzers for the hydrogen and fuel cell Supergen. My work spans catalysts, materials and improvements in the efficiency and longevity of fuel cells and electrolyzers. I declare two interests. I am a founder of two companies in this space. One is a fuel cell company and the other a grid-scale battery company.

To continue what Professor Russell was saying, the other areas in which fuel cells are being examined at the moment are associated with intermediate-temperature fuel cells, which operate at around 200 degrees Celsius. Maybe 15% of fuel cells manufactured at the moment are of that sort, and they utilise natural gas. One of the major fuels used by fuel cells at the moment is natural gas. but we are seeing a significant drive to move to utilising hydrogen as a fuel.

It is important to point out that fuel cells also have a useful mirror in electrolyzers. We are not going to talk very much about hydrogen today, but of course electrolyzers are a very important way of taking green electricity and producing hydrogen. An electrolyser is just the reverse of a fuel cell. A lot of what is learned in fuel cells can actually be applied to

electrolysers and vice versa, including manufacturing and other aspects like that.

Professor John Irvine: I am from the University of St Andrews School of Chemistry. I am a co-director of the Supergen in hydrogen fuel cells, but I should also mention that I lead the sodium-ion Faraday challenge project, and I lead the hydrogen accelerator for the Scottish Government. So I have a foot across all the camps and I certainly talk to lots of other people across the technologies. The last talks were a bit misleading; we do work together. Especially when it comes to scaling up and translating from lab to market, there is a huge crossover between all these technologies, and we should all work together.

Andrea and Anthony have probably answered the question about the different types of fuel cells available at present. The challenge is the fuels of the future. When you have hydrogen in every home, there is a very different need for hydrogen fuel cells. A lot of opportunities will come very quickly.

The Chair: Professor Irvine, it is probably my hearing, but your voice is sometimes very soft and you sound very distant. Could you improve on that, please?

Professor John Irvine: I will try.

Q33 **Lord Mitchell:** As part of our briefing notes for this session, we were given a table that showed the different fuel cells and their pros and cons. It was really interesting, and I suppose, like many things in science, it is all to do with the balance—the balance of cost, the balance of risk and so on. In this climate, particularly with the headlines today, safety seems to be one of the issues—that is, the safety of storage and noxious gases being produced.

Is this an issue that you consider a lot? Is there perhaps a case, given what we have seen with the Oxford AstraZeneca vaccine, for somehow pre-empting the public relations that may come with the development of fuel cells?

Professor John Irvine: Safety is much more to do with the fuels. Electrolysis, which Anthony mentioned, is a really important part, and if you do not make sure to separate the oxygen and hydrogen, that is a high risk. There have been accidents in Korea from that. With the hydrogen accelerator our mission is to ensure that that does not happen because, as you say, with accidents like that you ruin the advance of new technologies.

In terms of noxious gases, I would not say that fuel cells have cons; they have lots of pros. You have horses for courses. PEM fuel cells are really good for transport. Like most fuel cells, they have very low emissions; indeed, they have no emissions at the point of use. You want fuel-cell transport not just because of energy security; it is because you can have these large vehicles in city centres without creating emissions.

Q34 **Baroness Rock:** I have no interests to declare for this inquiry. I would

like to come on to applications and ask the witnesses about the current uses of fuel cells in the UK and what makes them suited to those applications. We have just heard from Professor Irvine, and in the previous session, about fuel cells and batteries being complementary to each other. I would like to understand a bit about the advantages and disadvantages of using fuel cells over other technologies such as batteries. Could the witnesses also touch on what fuel cells are used for in other countries? I understand that in Japan fuel cells are often used for heating applications.

Professor Anthony Kucernak: In the UK, fuel cells are predominantly used in transport such as cars and buses—and trains to a limited extent, although that is growing. There are also some stationary applications similar to the ones that you mentioned in Japan, where fuel cells utilise natural gas and produce electricity. The extra heat generated is then used to heat hot water. As a result, you get very high effective efficiencies of conversion of natural gas to useful electricity and hot water.

I suppose the demarcation between batteries and fuel cells comes from the size of the vehicles that fuel cells are used in and the distance with which they have to travel before refuelling. Looking at the world usage of transport fuels, about two-fifths is petrol and two-fifths is diesel. You can broadly say that batteries are suited to vehicles that use petrol and fuel cells are suited to those using diesel—the bigger vehicles such as buses, trucks, trains and ships.

That is quite a good demarcation between the scales, and it has to do with how the fuel cells scale to much larger systems. They become more efficient as the system gets larger, and that will probably remain so in future. Transport will be roughly split down the middle—in a similar way to the way we have petrol and diesel at the moment—between battery electric vehicles and fuel cells, with the proviso of course that every fuel-cell vehicle also has a small battery in it. Everything requires batteries. There is also the possibility of using different fuels, not only hydrogen, but ammonia.

As you mentioned, in Japan there are 350,000 home fuel cells at the moment, so quite a few have already been deployed. They provide hot water and electricity to houses. Some of them also operate in a grid independent mode, so they can operate for 72 hours without any electricity. They can provide emergency electricity in the event of a grid failure.

Baroness Rock: We talked about Japan. Are any other countries utilising this effectively?

Professor Anthony Kucernak: Something like 60% of fuel cells have been deployed in Asia at the moment, not only in Japan but in South Korea and that general area. About one-third of fuel cells are being deployed in North America and about 10% have been deployed in Europe. That gives you a scale. That is in terms of the power production of the fuel cells, not the number of them. Most of them, probably around 75% or so, are actually in transport applications at the moment.

Baroness Rock: Thank you. Do you have anything to add to that, Professor Russell, perhaps in relation to other applications and not just transport, although that is obviously an important area?

Professor Andrea Russell: If you look at Professor Kucernak's analogy of where you are using diesel you would use a fuel cell, then a fuel cell would be a suitable substitute in anything using diesel. This could be localised power generation on building sites. Yesterday, we discussed their use in factories for moving goods around. If you could use a diesel generator, you can use a fuel cell.

Baroness Rock: Professor Irvine, would you like to comment any further on this?

Professor John Irvine: The question of which is better, batteries or fuel cells, is the wrong question. It should be: how can we make these work best as a culmination of technologies? I strongly believe that. For example, we are demonstrating a hydrogen train for COP 26, and that has a big battery. It gives you the power to some extent, but the distance comes from hydrogen fuel cells. They work very much together.

Baroness Rock: Thank you. Lord Chair, I have nothing further to ask.

Q35 **Lord Sarfraz:** Professor Russell, where are we going in fuel cell technologies now? Will they become smaller, cheaper, more efficient and longer lasting? Where is the technology headed in the next few years and then over the next 10 years?

Professor Andrea Russell: The brief answer to all your questions is: all those things. We can make fuel cells smaller depending on the application. I would argue that the better utilisation of fuel cells is with the larger ones, in integrating that into the whole system—making localised use of hydrogen that is produced. The advances are in integrating the fuel cells into the whole network.

Greater work needs to be done on the interior part of the fuel cells. There is more work to be done on developing different membranes to work at different temperatures so that we can make use of a greater range of fuels, improving the durability of those systems. That is where it is going: in both smaller and larger technologies.

Professor John Irvine: The biggest offering from fuel cells is that they can generate electricity at high efficiency in decentralised systems. Local megawatt generation is much more efficient than you would have otherwise. Decentralising and making the system more robust is very important as we move into the new energy systems.

Lord Sarfraz: What should we not expect? What are the limits of fuel cell technologies?

Professor John Irvine: A big driver is the availability of fuels like hydrogen, and the need in something like shipping. We cannot propel long-distance shipping the way we have in the past with all the emissions. We are looking at fuels like ammonia, and you can deliver

longer range than if you use simple hydrogen. In high-temperature fuel cells, you can use ammonia directly to provide electric drive.

Marine transport requires more than 10% of the world's consumption in the transport sector. Pollutant emissions at sea are currently greatly exceeding allowed levels, so we really need clean fuels such as methanol or ammonia. With fuel cells, you get 50% more drive energy from the same amount of fuel. Unfortunately fuel cells are very expensive at present, but as they get more into the market they get cheaper and cheaper. We are still at the start, obviously, but the costs can come down very quickly as we develop more, and there is no reason why that cannot be done in the UK.

Q36 Baroness Brown of Cambridge: Various people have mentioned that fuel cells are very efficient, and I would like to explore the efficiency question. We are talking about using very expensive fuels like hydrogen or ammonia, so how high can we push that efficiency? In particular, how high can we push the efficiency of low-temperature fuel cells? I understand that the high-temperature fuel cells are significantly more efficient.

I would like to understand where we are with efficiency and where we are going, because if we are using very expensive hydrogen fuel—green hydrogen fuel, for example—we absolutely need all the efficiency that we can get. Can we start with Professor Irvine perhaps?

Professor John Irvine: With hydrogen, we are targeting \$2 a kilogram.

Baroness Brown of Cambridge: I want to understand the efficiency of the fuel cell, not the cost of hydrogen.

Professor John Irvine: I do not entirely agree that green hydrogen will be that expensive for very long. There is so much happening in the North Sea, so you should really watch that space. The efficiency is because there is no mechanical operation in the drive. That means that, depending on the chemistry, you can get up to 70% of the chemical energy to come back into electrical energy. In a typical gasoline engine 15 years ago, that was maybe only 15%.

Baroness Brown of Cambridge: I do not want to compare them with gasoline engines. I want to know how far we can take the efficiency of fuel cells.

Professor John Irvine: It is probably how you use the fuel cell. Academic studies and bidding contests produce really small devices with really high efficiencies, but where there is already high power you want to balance all these things in development. The inefficiency in a fuel cell is heat, so you need to reuse that heat to make the system simpler. Take combined heat and power, for example. There are five CHP units at St Andrews that produce heating as well as electricity.

Professor Anthony Kucernak: I agree with Professor Irvine that utilising waste heat allows us to increase the efficiency up to maybe 97%.

That might be a benefit of using fuel cells in places like homes or coupled with industrial usage.

The other point to note is that the fuel cells generated at the moment are optimised for transport, so they are not necessarily optimised for efficiency. In the low-temperature fuel cell they are more optimised to be used in a transport setting—that is, to achieve the largest power density possible. If we are going to generate fuel cells or make fuel cells for energy production, for instance in power plants, we can quite easily improve the efficiency by decreasing the power density (ie there is a tradeoff between power density and efficiency).

Long term, there is a goal of efficiencies of over 70%, which seems reasonably achievable. The longer-term goal is for fuel cell systems to be down to \$10 per kilowatt hour. There is a significant opportunity for fuel cells to hit both high efficiency and low cost.

Q37 Baroness Sheehan: I would like to explore further the challenges of advancing fuel cell technologies. Last week we heard that one of the key challenges is cost. Could we explore that a bit more? For high-temperature fuel cells, another challenge is the degradation of the cell components. Could we also address that issue? We will come back to Professor Russell on catalysts.

Can we start with Professor Irvine, and then Professor Kucernak?

Professor John Irvine: I am the right person for high-temperature degradation. There are two answers to that. One is developing new materials that are more robust. The other, perversely, is getting higher performance so that we do not have to operate near degradation limits. We often run fuel cells at 0.7 volts for highest power per unit area, but where the degradation is a lot worse. Historically SOFCs ran at 0.9 volts, which is a lot more efficient for conversion, but with limited power. Effective fuel cell systems must run for a long time. The Westinghouse systems that used this high voltage have been running for 10 years without a lot of degradation. Everything is tied in: if you can get the cost down, you can afford to run the fuel cell closer to open-circuit potential. You get a bit less current density but much longer durability and much more efficiency.

Professor Anthony Kucernak: I will leave the discussion about catalysis to Professor Russell, because she is probably best suited to answer questions on that.

In terms of the development of new materials for fuel cells, there are significant opportunities, especially for low-temperature fuel cells. There are membrane materials that are utilised to make them thinner and stronger, which would improve the longevity, performance and efficiency of fuel cells. Hydrogen storage is an area that requires further research in order to reduce the cost of the storage and improve the efficiency and density.

The manufacturability of fuel cells is an important area. I am working with a fuel cell company on new technology to allow the large-scale

manufacture of fuel scales quickly and efficiently, and that is quite an important aspect.

Better integration of fuel cells with electrolyzers and utilising the hydrogen from those electrolyzers is also an important challenge, because we can increase the round-trip efficiency of the conversion of renewable electricity to hydrogen and then convert that hydrogen back into electricity where and when it is needed by tweaking the integration of those two systems.

Finally, I want to mention redox flow batteries, which are similar to fuel cells but are midway between fuel cells and batteries. That is an intermediate technology that also has a lot of opportunity in future.

Baroness Sheehan: What are the challenges in addressing those opportunities?

Professor Anthony Kucernak: The challenges are in new materials, testing and fundamental understanding. In the UK, we have some world-class electrochemists and world-class people working in materials chemistry on understanding those sorts of materials. We have the ability to do very good modelling and simulation of fuel cells, and there is a requirement to better develop those models to understand where the losses are occurring within the fuel cell so that we can improve the efficiency of those systems.

Baroness Sheehan: Are the potential rewards worth putting a lot of resources into this?

Professor Anthony Kucernak: There are significant rewards. The efficiency of a low-temperature fuel cell, for example, can easily be increased by 20% by optimising systems. It is important to realise that the fuel cell market is growing very quickly at the moment; it has grown at about 40% to 50% per year over the last five years. So fuel cells very much have an opportunity to fulfil the requirements of replacing diesel-powered equipment by 2040 or so at the rate that it is growing at the moment.

Q38 **Baroness Sheehan:** Professor Russell, what are the challenges in catalyst development? What are the prospects of developing cheaper and more stable catalysts?

Professor Andrea Russell: The challenges in catalyst development are down to the fact that most of the fuel cells are primarily the lower-temperature PEM—polymer electrolyte membrane—cells. In that case, it is mostly platinum group metals that we are using as the catalyst. They are expensive, and we look at the degradation of those and whether they maintain their activity.

There has been quite a long series of work now on trying to improve the stability of those catalysts while maintaining activity. There is always the trade-off between improving stability and keeping activity. There are some exciting developments, such as developing the support which the platinum group metals catalysts—the nanoparticles—sit on in order to stabilise those and still maintain that activity. So it is about moving away

from just carbon-based supports to nitrides, metal carbides and things like that.

In terms of the catalysts and moving to other ones, it is really down to the development of the membranes. Can the membrane cope with the non-platinum-based material? By accessing other membranes, we may be able to move to more alkaline conditions, in which case the non-platinum group metals such as nickel and so on become much more viable catalysts. The investment there needs to be in the membrane, not necessarily the catalyst.

Baroness Sheehan: What materials are the membranes made of?

Professor Andrea Russell: In the polymer electrolyte membrane fuel cells, the general polymer is a fluorinated hydrocarbon, with acidic sidechains that allow the protons to be transported through it.

Q39 **Baroness Walmsley:** I have no interests to declare. What are the challenges in scaling up fuel cell technologies from the lab to wider-scale manufacture and usage—for example, in engineering, infrastructure, availability of fuel, costs and safety? Can we learn anything from how this has been done in battery technology? A national standard commercialisation pathway for batteries was suggested by an earlier witness, and I wonder whether that would be relevant for fuel cells too. Perhaps I could go to Professor Irvine first.

Professor John Irvine: I am not quite so optimistic about the scale-up in batteries, because I am working very hard to scale up sodium batteries and we are setting up significant scale manufacturing.

In particular, we really need a supply of materials for scale-up. Going from lab to bench, you need large quantities of very well-defined small particles—[*Inaudible.*] In our work in both fuel cells and batteries, we found it really hard to source these, even in Europe, never mind in the UK. There is a lot of challenge in scale-up. It translates right across these technologies. The way we make batteries for power cells is very similar to the way we make ceramic fuel cells and also to coat the fluorinated polymers that Andrea just mentioned. So there are a lot of commonalities and much to share.

That is the bit that we keep missing in UK research and development. We really need to be able to go to that next step, especially with fuel cells. I am somebody who likes to discover new materials and do exciting solid-state chemistry. I would like to see it go that bit further. Tony has done great work at Bramble and in taking technology to low-cost application. However, we just do not do enough of that. It is very hard to do that in the academic sector. As Serena said earlier, there are a lot of possibilities there.

Professor Anthony Kucernak: At the moment, the fuel cell industry is relatively small, for instance compared with the battery industry. Last year, about five or six gigawatt hours of fuel cells were shipped, which is actually small compared with batteries. As I mentioned, that is growing quickly at the moment.

As a result of that, when you build a fuel cell system, a lot of the components that you use are not optimised for those fuel cell systems. You have to use off-the-shelf components and, because of that, you take a bit of a hit on the efficiency. As the fuel cell industry grows, manufacturers that are producing the components that you need around within the entire fuel cell system will start optimising their components so that you achieve better efficiency in the entire fuel cell system.

In terms of start-ups and the way that fuel cell companies grow, obtaining inward investment has been quite difficult over the last 10 years, although that has changed relatively recently because of the big change in the interest in hydrogen. To take something from the laboratory and spin out a company has actually been very difficult, as I know from personal experience.

In terms of producing some of the materials, we have world-class materials manufacturers in the UK. Johnson Matthey makes components for fuel cells in the UK and it has shipped them all over the world, especially to south-east Asia. As was just mentioned, it has just announced that it is producing a new production line for materials for electrolyses, which, as I mentioned before, are very similar to fuel cells.

So we have the potential of having a good supply chain in the UK. We already have people working in that field, producing materials at a large scale, but it needs to grow.

Baroness Walmsley: When it comes to hydrogen, it is about not just the supply but the storage—that is, the quality of the tanks that are needed to store it in. Does that add a considerable cost to many of the applications?

Professor Anthony Kucernak: That is a very good point. Of course, the hydrogen storage for transport applications relies on carbon fibre tanks—the same materials used in Formula 1 cars. As a result, that is quite an expensive technology at the moment. There is a requirement for the production of that and the scale-up and the production. The belief and all the work I have seen shows that that mass scale-up will reduce the cost of those materials significantly. Having good hydrogen storage is very important.

One point I want to make about the growth in fuel cells is that, if we follow the current trends—for the last five years, we have seen this 40% or 50% increase per year—by 2040, we should have produced enough fuel cells to equal the world's cumulative electricity production. You can see that we are actually on trend to produce significant volumes of fuel cells, but in order to achieve that goal requires all that manufacturing happening in the background and factories being built. That is the potential goal, and the challenge is to make sure that it happens.

Professor Andrea Russell: One of the great limitations is the training in electrochemical engineering. If you want to implement batteries and fuel cells into the whole system, we need the source of those trained people. We are very good at training people in the chemistry. I would say that, in electrochemistry in the chemistry sense, we in the UK are world leading—

indeed, world beating. However, in terms of electrochemical engineering, we have a few groups and a few places where people are being trained, but that needs to be far more widespread. That is where I would put my money.

Baroness Walmsley: I have been hearing about the shortage of chemical engineers for decades in this country, I am afraid.

Professor Andrea Russell: I am being more specific than that: I am saying electrochemical engineers. It is truly not the same.

Q40 **Baroness Walmsley:** Thank you. Could you all look into your crystal balls and tell me which of the current early-stage technologies in the lab are the front runners? Will they be ready in time to contribute to achieving our target of net zero by 2050?

Professor Anthony Kucernak: As I mentioned with regard to the growth, there is the historical joke about fuel cells, which was told maybe 20 years ago, that fuel cells will be here "in five years' time". That was the joke, and it kept on being repeated for a number of years. Now is the time when you see that fuel cells are being deployed in very large numbers. You can drive in a fuel cell car; we have one at Imperial College and I have gone for a drive in it. We are seeing massive deployment occurring at the moment, and we are at the point of this exponential growth in the production of fuel cells.

In terms of what is in the lab, not only do we have good fuel cells systems available at the moment, solid polymer and solid oxide fuel cells, but there is a golden area in the middle, at intermediate temperatures, operating at maybe 200 to 300 degrees Celsius, which would allow us to improve the efficiency of the fuel cells. Also, the heat that you produce with those fuel cells at around 200 to 300 degrees Celsius can actually be very useful in other processes. That is a golden area where research in the laboratory might give really significant gains.

The thing about those systems is that you do not need to use platinum group metals as the catalysts, either. You can look at deploying systems at very large scale without platinum usage issues.

Q41 **Viscount Hanworth:** The use of natural gas in fuel cells is hardly favourable to decarbonisation, so is the transition from fuelling fuel cells with natural gas to fuelling them with hydrogen ammonium straightforward, or might there be difficulties there? Finally, is the use of ammonia simply a matter of improving safety, or are there other motives for using it?

Professor John Irvine: The efficiency of converting natural gas in a fuel cell means that you produce half as much CO₂ for the same amount of electricity, so it is an important step along a pathway. Ammonia is a very good way of storing hydrogen. You can store much more hydrogen in the same volume and move it much more easily. So a liquid store like ammonia is ideal for shipping. There are really exciting applications of new technologies for utilising ammonia as a fuel in shipping. There are some concerns about ammonia leakage being an issue, but it is already

widely used: it is in the top five chemicals that we use throughout the world. It is synthetic ammonia; it is not ammonia produced from natural gas.

Q42 **Baroness Warwick of Undercliffe:** My question follows on very nicely from the comment made by Professor Russell about integrating fuel cells into the wider energy system. Perhaps she would like to kick off on this question. In what ways could fuel cells be integrated in the UK—for example, in the electricity grid or heat production? Perhaps she could then talk about the technical challenges associated with using fuel cells for those purposes.

Professor Andrea Russell: If we look to the Far East, they are already integrating fuel cells into their systems. When you get hydrogen available and combined heat and power units, using fuel cells makes a lot of sense. I think there are over 200,000 deployed in Japan. That is a clear place where fuel cells fulfil that niche very well.

I will hand over to Professor Irvine to talk about the grid systems, because he has better knowledge on the larger fuel cells.

Professor John Irvine: I would like to mention Bloom Energy in the US. Its market is in looking at up to one megawatt fuel cells, which gives the grid independence that has become really important. Think of these larger systems as operating units. The chemistry building that I am in could be powered using a fuel cell. It is currently on natural gas, but if you can convert that to a hydrogen grid, a biogas grid, or biogas-hydrogen grid, these fuel cells will give that sort of delivery without net CO₂ emissions. Those applications are already quite well spread throughout the US.

Baroness Warwick of Undercliffe: What are the challenges associated with that?

Professor John Irvine: The more complex fuels have more chemical sensitivity, so you need to develop electrodes that are more robust with slight changes in the chemistry. You can also manage the system. In high-temperature fuel cells, hydrogen is quite exothermic, so you have to redesign the fuel cell from a natural gas system or cool it by converting the natural gas in situ.

Baroness Warwick of Undercliffe: Professor Kucernak, do you want to add anything to that?

Professor Anthony Kucernak: In terms of the wider UK energy system, the ability to use fuel cells to take care of some of the problems of intermittency of renewable energy might become very important in future. Lots of work is being done to look at, for instance, salt caverns for hydrogen storage and the ability to store renewable energy for days or weeks of the UK's electricity requirement. Putting that hydrogen back into a fuel cell might be very useful in dealing with the intermittency issue when the sun does not shine or the wind does not blow.

There is the opportunity to site fuel cells in local areas. A one-megawatt fuel cell system about the size of a 20-foot standard shipping container would power about 160 homes. That is the sort of thing that could be easily used to delocalise electricity production in the UK, give greater resilience and offset the requirements for reinforcement of the grid.

There are lots of opportunities here. An issue is that, if you are going to site a fuel cell system in a local community, you have to worry about issues associated with the hydrogen. Luckily, these systems are very quiet and do not produce any pollutants. They only produce liquid water, so that should not be too much of an issue.

There are some very nice opportunities to be gained in future. Another issue is that you might be producing hot water, so being able to distribute that hot water around the local houses in a local heating network might also be useful.

- Q43 **Baroness Warwick of Undercliffe:** That leads into my supplementary question. We have been told by almost everyone that fuel cells and batteries can act as complementary technologies in the same system. In what ways can fuel cells complement batteries in supporting electrification in the UK?

Professor Anthony Kucernak: The difference between fuel cells and batteries are in the time scales they can provide power for. Typically, you would think of batteries helping the grid over seconds to minutes to maybe up to four hours. Longer than that, we might have redox flow batteries, which might go from four hours to 15. Fuel cells can fill in the much longer periods, potentially from a day up to a few weeks if you are using hydrogen storage in salt caverns. They are complementary in the amount of energy that is stored, the requirements and the number of times that you can use them.

Professor John Irvine: I forgot to say something quite important about the quality of power. I mentioned Bloom Energy, with companies such as eBay and Google using these high-temperature fuel cells in their facilities in California right on the front of the forecourt. Microsoft suggests the same approach for data centres. There is a very important role for fuel cells in supporting the distribution of data centres across the country.

- Q44 **Lord Winston:** Could I start with a supplementary question, as my allotted question has been partly covered already? Talking of transport, no one has mentioned fuel cells in aviation. I know that hydrogen has been tried a bit in aviation, but I wonder whether any of you would like to briefly mention what you think of that and the possible future, given that this is a very important cause of climate change? Professor Russell.

Professor Andrea Russell: I will hand over to Professor Kucernak, because he is the person to answer this question for you. You should have it from him.

Professor Anthony Kucernak: Airbus is working quite significantly in this area. Just a month or two ago it released plans and details of a fuel cell-powered aircraft that it would operate. The opportunity to utilise fuel

cells in aviation is quite important. There is, of course, a safety issue here, because you are taking liquid hydrogen on a plane. Looking at the designs of these planes, the rear third is where they store the hydrogen. Very careful risk assessments have to be performed to do that.

However, there is an opportunity to put fuel cells in those sorts of situations. It might make more sense for goods transports rather than passenger transports, because if there is an issue there it is less of a problem. In the longer term, fuel cells can grow into that space—much more so than batteries, if we are going to try and demarcate the two.

Lord Winston: Thank you. I think I had better stop there, otherwise I shall get my knuckles rapped by the noble Lord, Lord Patel. Fortunately, he is not very close to me, so there is not such a problem as there would normally be.

The Chair: There is no reason why I would do that. Carry on.

- Q45 **Lord Winston:** I will ask about the issue of research and development. I see from our briefing material that the EPSCR is running at about £8.5 million per year on grants for fuel cells. I remember when I was on the EPSCR that was about what we spent on fission and roughly what we spent on fusion too. It seems a bit strange that we are not spending more. Is that a fair comment?

Professor Anthony Kucernak: That is a very fair comment. If you look at the amount that is being spent on batteries at the moment, that amount should be spent more on batteries. Historically, there has been a countercyclical funding round, in that batteries get funded and fuel cells are defunded, and then fuel cells are funded while batteries are defunded. That helps neither area very much. There needs to be a continuous degree of funding. If you look at the potential difference that fuel cells can make to the UK energy system, it is as large as batteries. To be funding fuel cells at a rate much less than 10% of that of batteries at the moment is a bit crazy.

The UK was world leading in its fuel cell research. I would say that, at the moment, we are world-class—we still maintain world-class fuel cell research—but there is a risk, because of the funding climate for fuel cells at the moments, that we might drop below that. That would be a real shame. We have produced so many really interesting and useful technological advances and we have spun out companies: we have a number of £1 billion-class companies working on fuel cells and electrolyses at the moment. It would be a shame if we were unable to build on that and use the lead that we have in this area at the moment. On batteries, it is important to say that it is not a question of either/or; it is both.

Professor Andrea Russell: The fundamental electrochemical knowledge that you need to work in fuel cells and batteries is shared. When the funding agencies say things like, “Batteries are going to be a growth area and fuel cells or hydrogen are going to maintain or decline”, you shift those people into thinking about working in batteries, because they think it is more likely that they are going to get their funding. So you redirect

that effort. We need both. I hope that what we have said to you today is that they have their niches, and that if you really want to decarbonise by 2050 you need them both.

Professor John Irvine: There is a lot of funding at the present for demonstrating hydrogen, but even then there is almost no funding for hydrogen research. Over the last 10 years, either hydrogen or fuel cells have been labelled as reduce by the main UK funder, and new staff do not get appointed in departments in an area where it is not recognised as critical. This is more to do with some sort of historical finance management than any real science drivers.

I always thought that the UK was really good at long-term efforts. It is much better to have 10-year programmes than to have annual feast or famine.

Q46 **The Chair:** What would a Faraday fuel challenge look like?

Professor Anthony Kucernak: That is an interesting question. I suppose that we need to think about where the UK needs to be in order to decarbonise by 2050 and work back from there. We need to have a vision of what the energy network will look like, where our hydrogen is going to come from, how much of it we are going to have, and where we need to put our electricity generation from fuel cells. That probably drives an agenda of fundamental bottom-up research that then helps to support placing those fuel cells in different places.

At the same time, we need to interact very strongly with industry to make sure that we are developing the production and the assembly of the components in order to produce those fuel cells. There needs to be a strong coupling between the chemistry, the electrochemistry and the electrochemical engineering in universities and industry in making those components, assembling them and producing the systems.

Professor John Irvine: I would really like to see a very strong element of industry and academia being forced to work together. That is an opportunity that Faraday has missed. There is very strong academic and industrial funding, but at least a quarter of it should be tied to companies and academics working together, because the industry learns the opportunities and the academics learn the challenges. You can move a lot faster if you work together.

The Chair: If I may put the question another way, what would a fuel cell challenge look like?

Professor John Irvine: Addressing future fuels, such as ammonia, will be one of the important challenges—perhaps even for air transport, because it provides a lot more hydrogen than hydrogen with the same volume and mass.

The Chair: We heard previously, for instance, that ammonia and hydrogen can be combined for long-haul flights.

Professor John Irvine: Yes. That is certainly possible. I would not rule out synthetic green fuels or biofuels; I mentioned today news about NREL

and bio-derived fuels. For flight, batteries are the most difficult; they are the biggest stretch. Fuel cells may well make it, but you should keep on with green fuels, especially for the most challenging tasks as well.

- Q47 **Baroness Sheehan:** Last week, we heard about the potential for fuel cells to help with the domestic heating problem. Heat pumps are very difficult to retrofit, and 80% of the housing stock is going to need to be retrofitted. The Japanese are moving ahead with domestic heating, but where are those fuel cells being manufactured?

I really want to draw a comparison with China. We had a lot of very cheap solar PVs produced very quickly from China. Is China involved in fuel cell production and manufacture?

Professor Anthony Kucernak: Yes, China is aggressively going into fuel cell manufacture for both transport and combined heat and power systems. Combined heat and power systems are probably more Japan and South Korea. China is focusing much more on transport at the moment. However, China has some very aggressive national programmes to support the growth of fuel cells in a range of different areas. The Chinese view it very much as something in their future.

- Q48 **Baroness Brown of Cambridge:** I am interested to hear more about the UK industry that is going to be able to pick up and exploit your research. We have got Wrightbus buying fuel cells from Asia, and Alstom bringing us fuel cell trains with technology from Germany and possibly from Asia. Where is the UK industry that is going to be able to exploit this research, meaning that we get a benefit from it?

Professor John Irvine: There are several answers. As I am sure Tony will tell you, Johnson Matthey make the electrodes that go into those PEM fuel cells. Ceres Power is working with Weichai in China, one of its recent investors. There is also Korean investment in Ceres Power, so overseas companies are investing in UK companies. As I mentioned before in connection with sodium-ion batteries, that is a really interesting technology because it is something that the UK could take a lead on. We still have the opportunity in the fuels industry to emerge and take the lead on this.

Baroness Brown of Cambridge: We had Intelligent Energy, which is now pretty much overseas-owned, is it not?

Professor John Irvine: Yes, but Ceres Power has come from nowhere. LERC, which is located close to us, has come in from the US and is setting up in the UK to build a protonic oxide system for hydrogen production and utilisation. There are opportunities there, but we need to encourage them.

Professor Anthony Kucernak: We should probably also mention AFC, a company making alkaline fuel cells. There are some smaller companies, such as Adelan and Bramble Energy, which is one I am associated with and which is associated with the large-scale manufacture of fuel cells. Then there are also quite a number of integrators in the UK that are operating in the fuel cell space, such as Arcola Energy and Logan Energy.

They are developing valuable IP associated with putting fuel cells into systems.

So it is not just about making the systems; it is also about how you integrate them. There is lots of valuable IP that can be developed there, as well as things like software operation strategies, how you optimise these systems, and the balance of the parts and components that go round it, where quite a number of UK companies could contribute.

The Chair: At what scale are these companies? I wonder whether they are starting off here to take advantage of the good science and to build low-level manufacturing, and then, when it comes to high capacity, building somewhere else.

Professor Anthony Kucernak: If you are talking about the top tier ones—AFC Energy, Ceres, ITM Power—those are all UK-developed companies at market capitalisation of the order of £1 billion, that sort of scale.

The Chair: So they are unicorn companies.

Professor Anthony Kucernak: They do a lot of manufacturing in the UK, but of course they might offshore some of that as well at some point, depending on whether they can scale it in the UK. That is a commercial decision for them.

The Chair: Sure. We are just on time. I thank all three of you for coming today and making the time for us. We appreciate it very much. It has been an interesting and highly informative session for us. You will get a transcript of the session on which you can comment. If in retrospect you think there are some issues that you might have highlighted but did not, please feel free to write into us. Thank you very much for coming today. We appreciate it very much.