The Royal Society of Edinburgh

A Franco–Scottish Science Seminar organised by the RSE in collaboration with the French Embassy in London

Energy Conversion and Storage: Fuels to Electrons and Electrons to Fuels

Wednesday 21 October 2015

Report by Matthew Shelley

Scotland and France are each making substantial contributions to the scientific advances which are necessary to develop new and better approaches to clean energy generation, conversion and storage. This seminar brought together key figures from both countries to present and discuss new scientific ideas exploring their social, economic and commercial implications. The workshop took place amidst growing concern about whether the world is doing enough, and acting fast enough, to mitigate the impact of climate change by decarbonising the fuel and energy sectors in order to keep global temperature increases down to around two degrees centigrade.

Welcome

Providing a welcome to the event, John Irvine FRSE, Professor of Chemistry at St Andrews University, described it as an opportunity to meet, talk and exchange ideas. Much of the emphasis would be on the storage of energy as hydrogen.

Professor Irvine reflected on some of the key scientific breakthroughs related to hydrogen. It was identified by Robert Boyle, recognised as an element by Henry Cavendish and named by Antoine Lavoisier. Scotland's William Murdoch then played an essential role in the exploitation of coal gas (carburetted hydrogen) – which burns with a brighter light than hydrogen. Professor Irvine noted that this is a fuel similar to syngas in active composition, and in which there is renewed interest today.

Thanks were offered to the French Embassy for helping organise the event, which is part of a series intended to present areas of science where the two countries have a strong presence.

Dr Marian Beija, of the science and technology department at the French Embassy, added her own welcome to the speakers and audience. She explained that her department's roles include monitoring UK science policy, because it has the most efficient R&D and publishes the highest level of papers, with the greatest impact and for the least cost. It also provides support to encourage scientific collaboration.

Session 1

Introduction

Professor Michel Cassir, Professor, Chimie-Paris Tech and group leader of Interfaces, Electrochemistry, Energy (I2E)

Professor Cassir said the workshop had an important role to play in exchanging ideas around producing fuels and producing energy – "like charging or discharging a battery. So we will have both sides, speaking about renewable energy in a very large sense …"

He added that it provided a welcome opportunity to hear about some of the fresh thinking and new technologies which the sector badly needs.

The engineering of fuel synthesis from renewable power, and how it may inform scientific research

Dr Dimitri Mignard, Lecturer in Chemical Engineering, University of Edinburgh

Dr Mignard's prime area of interest is in straddling the divide between engineering and science, and in trying to advance practical ways of implementing the new technologies being developed by scientists in order to exploit renewables.

"When we look at electrons to fuels," he said: "we have to argue the case to get money to fund us." His experience has been that funders have not seen it as a priority area because they are focused on "low hanging fruit". Initiatives such as increasing energy efficiency have looked far more attractive because they have a greater potential impact for a lower cost.

Yet this cannot continue, according to Dr Mignard. Because "we have procrastinated for decades", much greater reductions in emissions are now necessary to limit global warming. "The message is basically this," he said: "fuel synthesis from low carbon power sources is one of the least cost-effective ways of reducing emissions; however, we are so late now that we have just got to do everything." Electrons to fuels will not displace fossil fuel-based electricity generation, but has its place in situations where the energy is readily available. Electrolysis is the current benchmark, but the economics are quite "tough". Other techniques are available, but come at a high cost. Research needs to be directed towards the most efficient possible use of electricity in the process, or it will be uneconomic.

Dr Mignard described a Scottish project, which has some French involvement, and which looks promising in terms of efficiency of conversion. The team has recognised the need to ensure they are working with electrolytes of sufficiently high conductivity from the start – so the emphasis is on creating systems that can be readily adapted to real-world production. The project is based on turning CO_2 to oxalate, as this only requires the transfer "of a couple of electrons for getting to oxalic acid and that can be converted to ethylene glycol, which is one of the building blocks of petrochemistry". The lower the number of electrons which need to be transferred, the higher the likelihood of an efficient process.

Dr Mignard went on to say that many mechanical engineers are cautious about the prospects for storing energy, as it needs a 70% round trip efficiency. A typical hydrogen for electricity storage scheme currently involves so many losses throughout the process that 40% is a considerable achievement. While acknowledging this as an issue, Dr Mignard believes it is as much one of PR as science and technology, because we are capable of close to 100% conversion of electricity to chemical energy. Even though most of the electricity is used to supply heat to the reaction, he believes that the building of a demonstrator model would do much to persuade people of its viability.

In conclusion, he said there is a great deal of exciting research which needs to be done; but, first of all, "we must show we are realistic about efficiencies". And it is also necessary to argue very forcefully that although these technologies are not "low-hanging fruit", the situation is so severe that they are now essential.

Composite molten salts/oxide as potential electrolytes in hybrid cells: an academic approach for applications in clean energy

Dr Armelle Ringuedé, Researcher, CNRS

Dr Ringuedé presented a variety of ideas about the use of composite electrolytes which have emerged from recent research. Among the topics she covered were future electrolytic cells and the potential for reducing operating temperatures. She also looked at issues such as durability and stability, which have profound consequences when attempting to develop practical systems. Dr Ringuedé described how composite materials made from molten salts and oxide phases offer high ionic conductivity.

She went on to discuss how fuel cells based on these kinds of electrolytes can achieve high power densities, though these have not been demonstrated over long periods of time. The results achieved by her group have been interesting and they have been attempting to understand the different behaviours observed. The central focus has been to explain the reason for the high power densities – mainly in terms of transport mechanisms. While some of the work has been through experimentation, there has also been extensive use of modeling. According to Dr Ringuedé: “The final goal of studies is to optimise single cell composition … and architecture”, with all the possibilities which that entails.

In conclusion, she described the current direction of research and the challenges that need to be tackled if it is to achieve its goal. Right now she is working on two different single cells. The potential applications for their research, she believes, could be extensive. Options include the creation of steam electrolysis cells to produce hydrogen, or to electrolyse CO_2 and hydrogen.

Discussion

Prof Cassir opened the discussion by saying that while the first two talks had been very different – one partly strategic and the other highly scientific – both pointed to crucial issues for “a new energy world”.

Dr Mignard was asked about how he felt it would be possible to communicate the importance of developing fuel cells to the man in the street. In addition, it was asked whether there is an overwhelming economic and policy case which can be argued for the creation of synthetic fuels and natural gas. One of the problems, it was suggested, is that the benefits come in a variety of ways, such as the possibility of getting carbon abatement, or for the reuse of existing infrastructures rather than creating new ones.

In responding, Dr Mignard said he believes that the backing of the man in the street is vital, not least because politicians are sensitive to their views. He pointed to the significance of electricity prices in the recent UK General Election. He suggested that promotion of successful projects, such as a Scottish one which has been developing fuel cells for domestic heat and fuel, would go a long way. But most important of all would be a demonstrator showing the efficiency with which electrons can be converted to fuels.

One of the main drivers for change which was discussed was around the impact on electricity prices. This, though, might be different in France as compared to the UK, as the widespread use of nuclear power and the structure of the energy market means that prices and emissions are lower. Dr Cassir suggested that this might change in the future as old French reactors need to be replaced.

Session 2
Emerging nanoparticles for energy conversion

Dr Dragos Neagu, Research Fellow, School of Chemistry, University of St Andrews

Better techniques for supporting metal particles on oxide surfaces could bring substantial advances in fuel cell technology. This would be of great value in the production of clean renewable energy and in the storage of excess energy as hydrogen, or other fuels. Dr Neagu discussed research comparing two techniques for placing metal particles on oxide surfaces, infiltration and exsolution, looking at how particles work in these approaches and what the consequences are.

"As you are probably all aware, metal particles supported on oxide surfaces are of great interest in a number of applications in the chemical industry and for different processes in energy conversion," said Dr Neagu. The interaction between the metal particles and the oxide support can be of tremendous importance. Advantages can be gained if the interaction can be improved and made more stable. The metal-supporting structures are usually made by infiltration, which involves coating the substrate with metal particles. Exsolution works in an inverse way in a process that brings the metal to the surface.

"Infiltration is a widely used and very flexible technique which can be used in many situations, but it is a bit problematic to use and to optimise, because it involves a large number of deposition processes to get the loading that you desire." said Dr Neagu. Due to this, it can be time consuming and wasteful; in addition, the interaction between the metal particles and support is not strong because it is quite superficial.

In exsolution, the particles are produced in a single step and already placed exactly where they are needed. Exsolution also avoids waste, because particle growth can be triggered where it's wanted. Dr Neagu said the main contribution to the field made by him, and his colleagues, has been in finding ways to trigger and enhance exsolution. He went on to describe research into the interface between particles and substrate using the exsolution and infiltration. With exsolution, the particles are embedded to around one third of their depth into the substrate, making the bond much stronger than with infiltration. The interface is also very smooth.

Tests of structures made using the two techniques have showed that those made through exsolution perform better under harsh conditions, such as high temperatures, making them potentially well suited for use in certain forms of fuel cell. Similarly, they are less prone to coking, which is a major problem for catalysts. Experimentation has also suggested that the techniques being developed by Dr Neagu and his colleagues could improve the efficiency of high-temperature electrolytic conversion.

Materials for protonic ceramics fuel cells

Professor Olivier Joubert, Professor of Chemistry and Materials, University of Nantes

Professor Joubert's presentation described the work and make-up of the HySPàC (hydrogen, systems and fuel cells) network in France. The network, which he has led for two years, holds workshops and promotes links between research groups. It currently embraces around 100 groups in 70 laboratories in the academic and industrial sectors and a total of 250 researchers, many of them electro chemists.

The main topics of interest are fuel cells, hydrogen storage and production, he said. Among the wide-ranging research interests of network members he listed stacks, high- and low-temperature fuel cells and systems optimisation, plus ageing and the anticipation and diagnosis of damage. There are also people working on ways to accelerate hydrogen uptake, release and high-volume storage. Further areas of interest include new electrolytes and electrodes.

Turning to one of the main challenges for fuel cell research, Professor Joubert said there is a need to find ways to reduce operating temperatures. Doing this could address difficulties with durability, degradation and cost of materials. The current difficulty is that reducing the operating temperatures while using the same materials which are effective in high-temperature systems brings loss of performance. The development of practical lower temperature fuel cells requires new materials, including solid-state electrolytes and electrodes, said the Professor. A big research drive into new electrolyte materials is already taking place, with some results already published, which show the benefits of reduced electrolyte thickness.

Tackling challenges such as this could be of great benefit for PCFCs (proton conducting fuel cells), which are widely seen as one of the most promising electric power generation systems, owing to their high conversion efficiency and environmental safety. The Professor provided a brief survey of types and properties of PCFC materials and some options for operating at low temperatures.

In conclusion, he re-emphasised the problems with existing electrolytes and the pressing need to discover new ones, and also to find new and improved catalysts.

Discussion

The question was raised of whether HySPàC has lessons that could be shared on how to involve industry partners in R&D. Professor Joubert said there is another network in France, which draws its members from large industry, and that despite attempts to engage with them, there has been little interest.

The suggestion was made that this might be because of different approaches to intellectual property – with academics aiming to publish research findings and industry wanting to keep them under wraps so they can be patented and commercially exploited.

Problems were also identified with accessing funding for fuel cell R&D. Professor Cassir argued that this may be because it is currently out of fashion and the way ahead could be to link it to work being done in areas such as wind and solar energies.

Session 3

Introduction

The afternoon session was introduced and chaired by Professor Joubert.

Electrochemical promotion of catalysis

Dr Philippe Vernoux, Senior Researcher, Institute of Researches on Catalysis and Environment (IRCE Lyon)

Effective catalysis is vital to the development of clean energy and fuel production using technologies such as fuel cells. Dr Vernoux discussed EPOC (electrochemical promotion of catalysis), which is also known as non-Faradaic electrochemical modification of catalytic activity (NEMCA). This is promising, both for boosting catalytic processes and for pushing back the frontiers of catalysis. The ambition is to develop practical ways to modify both the activity and the selectivity of catalysts.

Dr Vernoux described a series of EPOC experiments conducted by his group in Lyon. These are significant because of their success in using low levels of energy to “strongly activate the catalysts". They point to the eventual possibility of fuel cells which use a non-Faradaic process, reducing the power needed to produce clean energy and fuel. He gave examples of experiments making use of the NEMCA effect in relation to energy and fuel production. These were partly characterised by changes to the electronic properties of catalysts and the use of slow electrochemical reactions.

The advances have been substantial, including the creation of "the best catalyst in the world". However, despite showing that the action of catalysts can be influenced in a non-Faradaic manner, there is a long way to go. Nonetheless, it is hoped that it will prove possible to modify the electronic properties of catalysts in order to optimise catalytic performance for energy production. Dr Vernoux concluded on a positive note and said: "There are many issues to solve before going to the application, but I think this can be done."

Direct carbon fuel cells; technology overview and research opportunities

Dr Euan Bain, Lecturer in Chemical Engineering, University of Aberdeen

The goal for UK electricity is high efficiency and low carbon power generation, according to Dr Bain. In the mid-2000s, the UK's stated ambition was to raise the efficiency of thermal plant to 50–55% net, working at much higher pressure and temperature. But achieving this would be technologically very challenging.

In 2007, the UK Government issued a command paper highlighting the need to reduce fossil fuel emissions. Yet it is very unlikely that we are going to end our dependency on fossil fuels in the near future. Today, much of the country's electricity comes from gas and coal, with some nuclear and wind. By contrast, the vast majority of French electricity is from nuclear, plus 15% hydro. According to Dr Bain, these realities create major challenges for cutting CO_2 emissions.

Carbon capture and storage is one potential way forward but, according to Dr Bain, the amount of hugely expensive plant required for carbon capture at power stations threatens its economic viability. Direct carbon fuel cells (DCFCs) could provide a solution, not least because they promise efficiencies of 80% or above. A DCFC also produces flue gas of pure CO_2, whereas current plants emit a mixture of gases. This removes the need to separate gases out for carbon capture.

"Sounds like a winner to me … If you look at DCFCs compared to thermal plant, in terms of efficiencies they are much better, in terms of the flue gas you have pure CO_2, so you don't need all that supplementary plant," said Dr Bain. DCFCs are also potentially quite simple systems, which, as a chemical engineer himself, Dr Bain said is appealing as it allows for the creation of robust and long-lasting systems. He went on to show examples of DCFCs being built for testing and described their advantages and disadvantages.

Turning to the issue of R&D, Dr Bain said it is vital for researchers to show industry that any technology they are developing can work as well, and will be as durable, as current equipment. "These technologies don't fly until the research community can demonstrate to the guys who actually build and operate it that the thing can work."

In concluding, he appealed to the research community to focus on practical problems – such as the many issues which need to be addressed to realise the promise of technologies such as DCFCs.

Discussion

The issue was raised as to which parts of the world are carrying out the most research into DCFCs. Measuring on the basis of publications, Dr Bain highlighted the work at St Andrews, and also in places such as China.

He also pointed to a reduction in the number of papers being published, which may reflect a shift in interest towards shale gas. One potential advantage from this, it was suggested, is that taking time out to develop a new technology allows more time to perfect technologies such as DCFCs, which are likely to be needed as countries with coal reserves will want to exploit them at some point.

Questions were raised about how much research is taking place into the use of different fuels for DCFCs. Dr Bain said the range includes anything from coal to coconut shells, and there is also some work taking place on the use of some very expensive fuel sources, which he regards as potentially failing to make a worthwhile contribution to tackling real-world needs.

Session 4

The molten carbonate adventure in fuel cells and innovative topics

Professor Michel Cassir, Professor, Chimie-Paris Tech and group leader of Interfaces, Electrochemistry, Energy (I2E)

Molten carbonate fuel cells (MCFCs) “are a really big topic”, according to Professor Cassir. One reason for this is that they utilise cheap materials such as nickel and nickel oxide, with some chromium and aluminium.

Professor Cassir described how MCFCs work and their distinguishing features, including that CO_2 is part of the system. He said they have advantages, such as that the operating temperature of $650^{O}C$ “fits very well with the reforming process” of natural gas.

There are already 120 MCFC systems operating around the world and they are generating 250MW of power “which means that if it is not already an open market, it’s a niche market”. The technology has been proven through more than 43,000 hours of use and there is considerable know-how when it comes to manufacturing.

Among the drawbacks, said Professor Cassir, is that there are relatively few organisations involved in development – though there are centres in the USA, Germany, Japan and Korea. Nonetheless, he argued that molten carbonate systems are doing well relative to other systems. There is now a 60MW facility in Korea, which he said is of a scale that starts to become interesting to industry.

Advances round the world are improving performance; for example in Japan, where work has been taking place on a tubular system. In discussing the performance of MCFCs, Professor Cassir said there are a series of technical issues to be addressed in order to make components, such as the nickel cathodes, less prone to corrosion that “little by little can kill the system”. Professor Cassir said that work has been taking place which shows the feasibility of steam electrolysis in MCFC-type systems and that co-electrolysis of H_2O + CO is becoming increasingly attractive. The valorisation of CO_2 by electrolytic reduction into CO has also been explored and should become a major challenge in future.

Turning to the issue of CO_2 emissions, he said the situation is becoming “delicate” and that action is needed. Upstream, there is a need for greater efficiency by using fuel cells or different fuels. The impact of this will be limited, so we need to develop approaches such as carbon storage. What would be even better, argued Professor Cassir, would be to recover and valorise CO_2. Fifteen years ago such an idea was seen as absurd, but now there are systems that can do it; for example, in Norway.

The Professor concluded with a review of a range of technologies and approaches which are being explored around the world, identifying some of the potentials they offer for producing clean energy and fuels.

Solid state electrochemical conversion of CO_2 and steam to fuels

Professor John Irvine, Professor of Chemistry, University of St Andrews

Using the area round St Andrews as a microcosm, the Professor highlighted a series of problems and potential solutions for generating clean energy and cutting carbon emissions.

Licences are in place for offshore wind farms in St Andrews Bay which could generate 5GW of electricity – enough to power Scotland. If these go ahead, something Professor Irvine expressed doubts about, given the direction of UK energy policy and prices, there is a huge drawback that there is only sufficient wind for two days out of three. “Five gigawatts that doesn’t work is no good,” he said and added: “If you can’t store energy then there is no financial case for this.” To make this possible requires storage on a huge scale.

Another feature of the area is that it has a large cement works, and cement production accounts for around 9% of global carbon emissions. The Torness nuclear power station is also within sight. “So, you have electricity from wind, you have grid connection and you have lots of CO_2. If you could convert CO_2 into a synthetic fuel you could really hit the CO_2 problem significantly.” He went on to say: “I’m not keen on capturing CO_2 from generation, but capturing it from cement production and converting it into something useful is really significant.”

If we are to think about managing energy, he argued, we need to consider not just electricity production but transport, chemicals and heat – “we need to think about moving energy into transport fuels or into chemicals”. The Professor cited examples of where this is being done; such as Germany, where wind energy is being turned into hydrogen and fed into the natural gas grid, thereby using existing storage infrastructure.

Turning to high-temperature steam electrolysis (HTSE), he described it as an environmentally friendly and highly efficient process to produce hydrogen using electrical and thermal energy. It is carried out using solid oxide electrolysis cells (SOECs), effectively using solid oxide fuel cells (SOFCs) in reverse.

Professor Irvine then described the latest developments in his group’s research. He also proposed the use of synthetic hydrocarbon fuels from water and CO_2 as an alternative to hydrogen as an energy carrier, to allow a carbon-neutral energy cycle.

To conclude, Professor Irvine reflected on Jules Verne’s idea that water would be the fuel of the future. “I don’t think it’s quite right to say that hydrogen is that magic bullet. It’s a contrary molecule and it’s very difficult thermodynamically. But there are other reasons why it is very useful. One is in storing energy to address intermittency, and you can use it for transport and for chemicals, in terms of private use, hydrogen transport is very important.” He also emphasised the value of CO_2 conversion to produce fertilisers, feed stocks and liquid fuels.

Discussion

There was interest in remarks made by Professor Irvine about producing ammonia, with questions asked about whether the process could be enhanced. If so, it was described as a potential “game changer”.

Asked about his comment that he is not keen on carbon capture from generation, Professor Irvine said it is possible to argue for that kind of process, but it requires very careful engineering to get all the energy flows right. His preference is for taking CO_2 from cement production and turning it into something useful. Professor Cassir speculated that the cement industry should be very interested in these kinds of ideas, as it is taxed on its emissions.

Final comments

Closing comments were made by Professor Irvine, who thanked the audience and said that the workshop had provided an ideal forum to get to meet and know colleagues from their own countries as well as overseas. He added that it was also a good chance for people to identify whether there were opportunities to develop new international projects, possibly through EU, UK or French sources. He also thanked the RSE and the French Embassy for organising the event and bringing everyone together.