House of Commons

Science and Technology Committee

Oral evidence: The role of hydrogen in achieving net zero, HC 1066

Wednesday 3 March 2021

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Watch the meeting

Members present: Greg Clark (Chair); Aaron Bell; Dawn Butler; Mark Logan; Rebecca Long Bailey; Carol Monaghan; Graham Stringer.

Philip Dunne, Chair, Environmental Audit Committee, attended the Committee.

Alan Brown and Alexander Stafford. Business, Energy and Industrial Strategy Select Committee, attended the Committee.

Questions 1 - 72

Witnesses

I: Professor David Cebon, Professor of Mechanical Engineering, University of Cambridge; and Professor Nilay Shah, Head of the Department of Chemical Engineering, Imperial College London.

II: Michael Liebreich, CEO, Liebreich Associates; and Dr Jenifer Baxter, Chief Engineer, Institution of Mechanical Engineers.

III: Baroness Brown of Cambridge (Professor Dame Julia King), Chair of the Carbon Trust and former Vice Chair of the Climate Change Committee.

Written evidence from witnesses:

Professor David Cebon, Professor of Mechanical Engineering, University of Cambridge – HNZ0020

Examination of witnesses

Witnesses: Professor Cebon and Professor Shah.

Q1 **Chair:** The Committee is now in session. The Science and Technology Committee begins its new inquiry into the role of hydrogen in achieving net zero. For this inquiry, I am very pleased to welcome to our Committee the Chair of the Environmental Audit Select Committee, Philip Dunne MP, and two members of the Business, Energy and Industrial Strategy Select Committee, Alan Brown MP and Alexander Stafford MP. Welcome to our proceedings.

I welcome our first two witnesses, whom I am delighted to introduce. They are Professor Nilay Shah, who is the head of chemical engineering at Imperial College London, and Professor David Cebon, who is professor of mechanical engineering at the University of Cambridge. Both are fellows of the Royal Academy of Engineering. Thank you very much for joining us and kicking off our session today.

I will start with an introductory question to both professors, starting with Professor Shah. How would you summarise the potential of hydrogen in achieving our net zero target and requirement?

Professor Shah: First, it is important to note that it is not the only way to get there. It is going to be part of a mix of solutions. When we look at either individual issues such as industrial clusters or the national energy and industrial system, we find that the overall cost and complexity of decarbonising is lower when you allow hydrogen to be part of the mix. In doing so, you see some specific roles for hydrogen in things like industrial cluster decarbonisation, the demanding road transport applications, decarbonising shipping and, potentially, aviation, either directly or as an input to synthetic fuel, combined heat and power, international trade in low-carbon energy storage—we can see a role for hydrogen there—and, importantly, seasonal energy storage, to allow us to store energy between summer and winter, in particular.

That is what we see coming through when we look at the whole-systems challenges of decarbonising the UK economy. We see some specific roles for hydrogen, and we see that if we allow hydrogen to take those roles, it reduces the overall system cost, as well as some aspects of complexity.

Q2 **Chair:** Is your central expectation that hydrogen will play a big role or a supporting role, given that you have described a diverse set of sources of supply?

Professor Shah: That is a really good question. When we do the analysis, the differences between what I would call a medium role and a large role are not as big as some of the uncertainties. Part of that will come down to some choices that we have to make.

I will give you one example. If, starting quickly, we are able to retrofit residential buildings, in particular, so that we can make them much more energy efficient—we may be able to change the size of the radiators—you will see a greater role for electrification of residential and maybe commercial heating. If we are struggling to get that retrofit programme working quickly enough, we will probably need to provide more thermal energy into residential buildings. That is an example of where the size of the role that hydrogen plays in the energy system will depend on the choices that are made around the built environment.

Where we see it being more stable is in things like industrial decarbonisation, demanding transport applications, seasonal energy storage and international trade. We see that as an area where it will play a very material role, but there is another area, particularly residential heating, where it will depend on the choices that we make around how best to go down that path.

Q3 **Chair:** You have talked about different uses, but there are also different means of acquiring hydrogen. Can you give us a brief summary of the different options here? There is what is often known as blue hydrogen, green hydrogen and grey hydrogen. Can you give us a potted taxonomy of those three?

Professor Shah: About 98% of the hydrogen that we make around the world is what we call grey hydrogen. It is made primarily from natural gas, oil or coal. It is made by reforming that into, primarily, hydrogen and carbon dioxide. Most of the carbon dioxide is released into the atmosphere.

To turn that from grey to blue, you have to capture the carbon dioxide and, ideally, store it underground. Fortunately, the capturing bit is an automatic part of the process because mostly, although not entirely, you are separating the hydrogen from the carbon dioxide in the bulk, but, at the moment, after that separation the carbon dioxide is just vented. If we integrate hydrogen production from those processes with carbon capture and storage, which we expect to come along as part of industrial decarbonisation and, to some extent, power system decarbonisation, and piggyback on that, it will give us access to blue hydrogen. That is currently the cheapest way of making low-carbon hydrogen. That can be made at scale and at a cost that could serve industrial feedstock and industrial fuel, for example. Just for reference, the cost of producing blue hydrogen may be in the range of £2 to £4 a kilogram.

Green hydrogen is made by using electricity in an electrolyser with water to convert the water into hydrogen and oxygen. Sometimes you can use the oxygen, but sometimes you cannot. That is something that is also being developed. It is the area where there is a lot of interest and where a lot of scaling and demonstration work is going on. Currently, that costs anywhere between £6 to £10 a kilogram. At the lower end of that price range, it would already be cost-competitive for buses, for example, as a replacement for diesel, so there is a lot of interest in green hydrogen, which has higher purity and is more expensive, as a transport energy vector. Blue hydrogen is probably seen more as a feedstock or industrial energy vector because of its larger scale and lower cost.

Q4 **Chair:** That is very clear and helpful. Before I go to my colleagues, starting with Rebecca Long Bailey, let me put more or less the same question to Professor Cebon. When you look forward into the future, what role do you expect hydrogen to play?

Professor Cebon: I have a rather different view to Professor Shah. The Achilles heel of hydrogen processes is inefficiency. With inefficiency comes cost. If processes are inefficient, you use a lot more energy. The consumer pays for energy, not for carbon, so if you use a lot more energy, it costs a lot of money. Ultimately, that ends up in the national bottom line, so an inefficient energy system is inefficient for the economy. For example, if the cost of heating buildings is very high, consumers have to provide that money or the Government have to provide some sort of subsidy, and there is no headroom for collecting tax. Therefore, energy efficiency is really fundamental to economic efficiency. That is a very important thing, because the Achilles heel of hydrogen is its inefficiency.

In my view, hydrogen should be used only in places where you absolutely cannot electrify. It is the Heineken of the energy system: only use it in places that electrification cannot reach. It absolutely has to be used for making fertiliser. Most of the world's hydrogen is used for ammonia fertiliser. We cannot do without that. That is essential to supporting the current population of the earth, so it has to stay. There are various industrial processes, such as making steel, where it is needed. It can be used as a reducing agent and so on. There are definitely industrial places for hydrogen.

Heavy goods vehicles can and should be electrified. Heating systems can and should be electrified. Coastal shipping can and should be electrified or hybridised. Aircraft and long-haul shipping are much more difficult. In those applications, there is a strong case for biofuels and e-fuels. Unfortunately, e-fuels are made from hydrogen, so they are even more inefficient and more costly than hydrogen. However, ultimately that is probably the only way in which we will be able to support aircraft. That is going to cause a lot of pain in terms of increases in the cost of flying. Those are the demanding transport applications. Hydrogen should definitely not be used for land transport applications, which can be electrified.

With all due respect to Professor Shah, his comments on blue hydrogen were not exactly accurate. The manufacture of blue hydrogen generates carbon dioxide in two ways. First, there is the process hydrogen. Professor Shah was absolutely correct to say that that can be captured easily. Secondly, the SMR process uses combustion of natural gas. It burns natural gas, and the carbon dioxide ends up in the flue gases, in just the same way as it does in a power station. Capturing that carbon is very difficult—much more difficult than the other stream. There are two different streams, and Professor Shah did not mention the second stream.

I would point out that, in his recent paper on this subject in September 2020, the statement is made that, at a maximum, 85% of carbon dioxide from the SMR process can be captured by CCS. That means that 15% of the carbon dioxide in the making of blue hydrogen is vented into the atmosphere. In that report, the way in which they compensate for that is by burning biomass, which is claimed to sequester carbon by growing fuel crops.

Chair: We will come on to that in a bit more detail.

Professor Cebon: It is very important that we realise that blue hydrogen is not green. It involves release of at least 15% of the carbon dioxide into the atmosphere.

Q5 **Chair:** We will go into this in a bit more detail. I am sure that Professor Shah will want to come back on some of those points. You have made very clear that you are sceptical about the efficiency of the use of hydrogen. Can you brief us on why it is ineluctably inefficient, as you see it?

Professor Cebon: It is about the fundamentals of the hydrogen process. On the green hydrogen side, the efficiency is really glaring. The process involves taking electricity, which is a very good source of high-quality energy, electrolysing water, which wastes 25% or more of the energy, compressing, storing and transporting hydrogen, which is a very difficult substance to process and to pump—it requires a lot of energy to pump—and then converting it back into electricity in a fuel cell, which is about 50% efficient. When you go around that process and multiply all those efficiencies together, you get a process that is about 30% efficient. That means that you get back 30% of the electricity you started with.

That is the fundamental issue. You are throwing away 70% of the energy in going from electricity to hydrogen and then back to electricity. That is in order to do things like store the hydrogen in salt caverns, to provide electricity storage and so on, and to pump it around the gas grid, it is claimed. However, the fundamentals of it are that the thermodynamic processes involved in hydrogen are fundamentally inefficient.

Q6 **Chair:** You have been very clear on that. That is very helpful. I have one final point before I turn to colleagues. What would you say to the argument that that inefficiency is mitigated, and perhaps solved, if the electricity that is being used is electricity that would otherwise be unused—for example, if it is from wind turbines offshore at times of low domestic usage?

Professor Cebon: The problem with the hydrogen economy is that a vast amount of electricity is needed because of this inefficiency problem. It is not going to be sufficient just to use the little bit that is left over on a windy day instead of curtailing it. That is the bottom line. Huge amounts of sustainable electricity are needed. The little bit of extra that is curtailed is by no means sufficient to make the hydrogen that is needed for the proposed uses of running heavy goods vehicles or heating buildings, which require absolutely massive amounts of electricity. You cannot just curtail a little bit and capture a little bit on a windy day. It just will not work.

Q7 **Chair:** Your evidence is very clear. If you really wanted to use it at scale, you would have to generate the electricity for it deliberately, rather than have it as a by-product of times when there was surplus. Let me go to my colleagues, starting with Rebecca Long Bailey.

Q8 **Rebecca Long Bailey:** Professor Cebon and Professor Shah, it is an absolute pleasure to hear from you both today. We have already talked about the role of hydrogen in the decarbonisation of heat. The maximum level of deployment of hydrogen, particularly no or low-carbon hydrogen, that looks feasible has been notoriously contested. We are getting into that today. Not least, there are the issues around suitability, the use of the transmission grid and the technical changes that would be needed to home boilers to process it. We can add to that points that have already been touched on—the shift in our homes away from gas power heating, in any event, to electric heating. I appreciate that this is a difficult question to answer, but what, in your view, is the maximum feasible level of hydrogen deployment for heating specifically? I put the question first to Professor Cebon.

Professor Cebon: I think that hydrogen does not have a place in heating. If it does, it is very niche. It is possibly in some industrial processes where you need high temperatures, although heat pumps will go to very high temperatures. The problem with hydrogen for heating is that it takes six times more electricity to heat a home using green hydrogen than it does to heat a home with a heat pump—six times. That comes from a combination of inefficiencies of hydrogen and the great benefits of using heat pumps, which give a multiplying effect called the coefficient of performance. That factor of six is really massive. It is why such a huge amount of electricity is needed to generate green hydrogen.

The alternative is the blue hydrogen route. With the blue hydrogen route, there are a number of problems. The first is that the energy content of hydrogen is much less than the energy content of the methane it is made from. That means that you have to pump a lot more hydrogen than methane if you are going to deliver the same amount of energy. It is about a third. You have to pump about three and a half times more hydrogen by volume. That means that you need much bigger pipes to transmit the energy and a completely different pumping system. You are talking about replacing the gas grid in order to pump the hydrogen because of the problem of the low energy value.

However, that is not where it finishes. The fact that you need so much more hydrogen because of the inefficiency—because you are losing a lot of the energy content by making hydrogen from methane—means that you need to import a lot more methane. The amount of methane imports really has to go up. In my calculations, for an overall hydrogen economy, you have to increase methane—natural gas—imports by about 30%. That will double the UK's imported natural gas, taking it to about 65%. That has a very serious implication for energy security. If 65% of the nation's gas is coming from imports, that is pretty serious.

The same point applies to the balance of trade. Because you are wasting so much energy in going through this hydrogen palaver, the result is that you have to bring a lot more energy into the country. The country has to pay for that. You have to import a lot more energy. It is very expensive, and you have to replace all of the infrastructure.

Q9 **Chair:** Professor Cebon, we need to keep the answers brief, I am afraid. We have a lot of questions, and colleagues want to ask questions.

Professor Cebon: Absolutely. The answer is that there is very little place for it in heating. Direct electrification of heating is far better, as per my initial point.

Q10 **Rebecca Long Bailey:** That is really helpful, Professor Cebon. Professor Shah, I put the same question to you.

Professor Shah: We have to be very careful about how we frame this question. A lot of the debate is very binary. The reality is that we are going to have a much more mixed energy system and it is going to vary a lot regionally across the UK. We need to keep that in mind. Some places will be almost entirely electrified, and some will have a mix.

When we did some work for the Committee on Climate Change, we found that one of the best solutions is a hybridised system, where the bulk of the heating is driven by heat pumps, but it is topped up by small boilers, which could be natural gas or hydrogen. They would not be used for that much of the year, but the point is that for about a month of the year you either need a heat pump that is really big for the rest of the year, and you need a lot of electrical generation infrastructure to be on for just that month, or you can top up the energy system with a chemical fuel. In some parts of the UK, certainly, a hybridised system is probably the best solution.

I come back to what I said at the beginning. What we find is that it has a role in the system, and its role is to reduce cost and complexity. It will probably end up being a big industrial heating fuel, because of the temperatures a lot of industrial processes operate at, but it will not be the primary fuel for residential heating. If it is used in residential heating, it will be in certain regionalised applications—for example, in regions that are industrial and have access to low-cost hydrogen anyway. In some places, the hybridised solution will be used. You will have a principal heating device that is a heat pump, but you will top it up for the colder month or two of the year because that is more cost-effective than having a big heat pump and a lot of electrical infrastructure that is needed for only a short period of time.

Q11 **Rebecca Long Bailey:** That is really helpful. I have one follow-up question. Both of you alluded to the fact that there needs to be a mix of heating options within people's homes. The political reality is that under the current frameworks we have millions and millions of people who have gas-powered boilers. Do you see a role for hydrogen, in a partial form, within the grid to bring us towards a transition to electrification of heat in homes? Is it easy to do that? Can you simply tweak a boiler, for example, to make that change, or does it require the same level of investment and change that an electrical boiler would? Would you need a completely new boiler?

Professor Shah: People are looking into this. A few per cent. is not an issue. The question that is being investigated at the moment is around what would be required for the 20% figure. Beyond that, you probably need a small tweak, not to the whole boiler but to the combustion system itself. That could probably get you to a reasonable level of blend. It certainly could be a way of enabling us to make a smooth transition, while also meeting our 2030 budgets on carbon, for example. Again, it would be only on a very regional basis. It would not be something that we would expect to see nationally. However, we might see it in places like the north-east of England, around Merseyside and in south Wales—places where we may be using hydrogen for other purposes, primarily, and then bleeding some of that into the local gas distribution network directly, without engaging particularly with the national transmission system, which is a bit more complicated with regard to hydrogen.

Professor Cebon: If you go to the department store, purchase a little electrical heater and switch it on in your house, it is a lower-carbon option than natural gas at the moment and would be a lower-carbon option than most blue hydrogen, if that were available. You can generate lower-carbon heat using the electricity supply that is already coming into your house by purchasing a space heater from John Lewis.

The idea that we should have hybrid systems consisting of hydrogen supply plus heat pumps surprises me, I have to say. It may be that you need to top up the heat in the winter. If you need to do that, use your immersion heater. It is much more efficient. You already have the electricity supply in your house. You do not have to have a whole hydrogen infrastructure to do it. If you are going to have a hybrid, when it is really cold, heat pumps should still have a coefficient performance of 3° down to about 0° or minus 5°. However, if it is really cold in the wilds of Scotland and you need a little more heat, turn on your immersion heater. The electricity supply is already there. You do not have to build a whole hydrogen infrastructure for that. That is a hybrid solution, I agree, but it is a hybrid electric solution, which is far cheaper than doubling up on your boiler—having a gas boiler and a heat pump, with a gas supply and all of that. That solution makes no sense at all to me.

Q12 **Graham Stringer:** I am sorry that I missed the first couple of minutes of the questions. Professor Cebon, in essence, you are saying that hydrogen can never compete, with the chemicals it is being made from. It will always be more expensive because of the energy loss. What interests me is how that translates into cost to the consumer. Are there any estimates of what the increased cost of using hydrogen would be to the consumer?

Professor Cebon: Yes. I can give you a great estimate on that. It comes from Professor Shah's paper in September on heating options. That is a careful analysis of heating options. It looks at hydrogen in all its varieties—the different ways of making it. It concludes that the total cost of heating by hydrogen—in the paper, they measure it by total annualised cost—is three times the cost of heating with natural gas. That is their paper, not my paper. Perhaps Professor Shah can comment on that.

For heating with heat pumps, the capital equipment is more expensive, but the energy costs are far less—one sixth of the energy cost of heating your home with hydrogen, for the reasons that I mentioned before. You have this complex calculation, which involves higher capital cost and lower running cost. However, that capital cost is sunk cost. It is an investment. Once you get on to being able to power your house with one sixth of the amount of electricity, you save that money pretty quickly. I am not an expert on the economics of heating, but the situation is that the total cost of ownership of electric heating is less. Blue hydrogen heating is at least three times the cost of natural gas heating, according to Professor Shah's report.

Q13 **Graham Stringer:** If you are using blue hydrogen, it is predicated on having carbon capture and storage, which has never had the consent of people in this country. Are the figures for the perhaps 60 sites that you would need for carbon capture and storage included in the figures in Professor Shah's paper?

Professor Cebon: You will have to ask him. I do not think that they are.

Chair: We should ask Professor Shah.

Professor Shah: The total cost of managing the carbon dioxide is also included in that.

Q14 **Graham Stringer:** So they are included, Professor Shah; thank you.

We live on a wet island—at least, we think that we do—but from time to time we have standpipes, warm summers and hosepipe bans in this country. What will be the stress on the water supply of moving to a hydrogen economy? I have seen estimates of up to 140 billion extra litres of water. Is that a realistic figure?

Professor Shah: It depends on which pathway we decide to go down. If we go down the green hydrogen pathway, I see that as growing quite gradually. There is a lot of interest now in doing that not with fresh water but, in the future, with seawater, possibly offshore. We would not see that happening at a pace that would create stress that would not be manageable, because the pace of green hydrogen development is likely to be fairly gradual over time.

If we adopt hydrogen for the purposes that I have described, we will see blue hydrogen taking the lead to get the hydrogen value chains up and running. You will need production, storage, transport and end use all to come on stream at the same time, as otherwise the system does not work. The green hydrogen that would come into that system would be phased over a fairly long period of time, which would give us plenty of time to understand and manage the water-related issues.

Q15 **Graham Stringer:** It is not the rate of change, is it? If there is more stress on the system and more water is demanded by industry and domestic users, won't it be a problem at times when—unusually, possibly—this country has a water shortage and the reservoirs are low?

Professor Shah: Yes, although in percentage terms the amount of water that you would be using would still be quite low relative to agriculture or domestic use, for example. I cannot remember off the top of my head how the figure that you mentioned relates to consumption, but I know that in percentage terms it is not a very large figure. You might have to take care in certain regions where there is more water stress, but it would not constitute a big difference to the overall water consumption.

Q16 **Graham Stringer**: We are discussing some of the uncertainties associated with moving to a hydrogen-based economy. Are there similar uncertainties in moving to the alternatives to hydrogen?

Professor Cebon: That is an interesting question. Let me transfer the discussion to my actual area of expertise, which is freight and logistics. In freight and logistics, an electrified transportation system has to operate in a slightly different way to one that is powered by diesel fuel. Vehicles have shorter ranges, for example, and you have to alter the way that logistics is done in fairly small ways in order to electrify it. There is still a reasonable level of uncertainty around exactly how that can be done. We have a very good idea, and we hope to run a demonstration project over the next few years to show how that can be done. That is an area of uncertainty. Things have to change a little bit.

One of the things about the electric economy compared to the hydrogen economy is that it is not quite so familiar. A hydrogen boiler is arguably more familiar to people because it is a bit like a methane boiler, and a hydrogen-powered truck is more familiar because it has a similar range to a diesel-powered truck. There is a little bit of uncertainty around that. What changes do you make to the organisation of, and energy provision to, the logistics system? That is an issue.

In the hydrogen area, the really big uncertainties are whether it is a good idea in the first place. It is not. It is better to spend the money on energy efficiency and on electrification. You have to answer the question, "What are the uncertainties?" It is very uncertain how hydrogen will be transmitted around the system without the gas grid, how much it will cost to upgrade the network, and particularly how you can scale the existing system to the amount of energy that is needed, either green or blue. In the case of green, massive amounts of electricity are needed. In the case of blue, it is a whole infrastructure for CCS, which does not exist in the UK, and it is a whole infrastructure for building salt caverns and salt caverns offshore so you can store hydrogen. There is huge uncertainty in all of that.

There is low technology readiness. The technology readiness for the electrical application is much higher. All of the pieces are well known. There is still some uncertainty, but that means that we can get on and do the electrical system right away. We do not have to do a lot more research.

In the next five years, we could get to a point where we can make the necessary infrastructure investments, whereas with hydrogen there are all kinds of uncertainty about how the gas grid will work, CCS, and how you will generate the amount of electrical energy needed in the long term. It is much more uncertain and a much longer-term project. My fear is that trying to get to the bottom of that uncertainty will cause great delay in the decarbonisation project—10 years. That is a problem.

Q17 **Graham Stringer:** The ordinary consumer, I suspect, would ask two questions. The first question would be about cost. The second question would be about the safety of hydrogen. When I worked in a laboratory, hydrogen came in red bottles. It is intrinsically a hazardous gas with a low ignition energy. Is that a problem that can be overcome either with the public or its intrinsic dangers?

Professor Shah: I should remind everybody—maybe some of you will remember—that, up until the 1970s, a lot of houses ran on what we call town gas, which is arguably a lot more dangerous than hydrogen. People were educated in the safe use of that gas. A lot of gas safety regulations would need to be followed at the infrastructure level; but for devices at the household level, if the fuel were to be used, certain things would be put into the system like colourants and odorants to ensure that you would have the same level of safety. Codes are being developed.

It is very important to talk about the cost. In our studies, many bodies such as the Committee on Climate Change, IRENA, IEA and IIASA have looked at the question of regional and national energy systems. They all find that, if you include hydrogen in the mix, the overall system cost is lower because it has certain roles to play in the system. However, if the low-carbon energy system cost were the cheapest thing, we would be doing it today. The reason why we do not have a low-carbon energy system and we talk about cost is because we are not really costing energy. We are not paying the proper price for energy today as consumers of energy or of industrial products. We are sharing that cost with our children and grandchildren. When we say today's system costs this much, and the low-carbon system will cost that much, we are not comparing the same things.

If we had a low-carbon system today, then at least each one of us as consumers would be paying the true cost of what we consume rather than sharing it with future generations. We have to acknowledge that, with the current economic model that we have, a low-carbon system will be a bit more expensive, and that is because our economic model is wrong. However, by 2050, a low-carbon energy system, to the consumer, will be a lower fraction of the household budget. That is a really important point to make. Whichever path we go down, it will look more expensive in absolute terms as a fraction of disposable income. Even the low-carbon system will be a lower cost to the consumer as a proportion of household budget.

Q18 **Chair:** What about the safety point that Graham raised, Professor Cebon?

Professor Cebon: Hydrogen also has safety issues. I am not an expert, but I do know about the heavy vehicle industry. In that industry, a lot of diesel is shipped around the place. At diesel refineries, great precautions are in place, with trained operators pumping fuel, earthing their vehicles, with all kinds of restrictions, such as ADR constraints on how the system works.

With hydrogen, that very dangerous situation, which is highly controlled in the refinery, is shifted to the forecourt of the petrol station. Now we have completely untrained people pumping hydrogen into cars or trucks. It is dangerous and invisible, it has an invisible flame, and it is highly explosive—far more explosive than petrol or diesel. There are some real issues there, but, as I say, I am not an expert in that area. I would just point out that we are going from a tightly constrained system to one where all kinds of different people are handling the dangerous substance, and that has not really been thought through.

Chair: Thank you very much. Let me go to Alan Brown.

Q19 **Alan Brown:** Professor Cebon, you are quite clear about the need to electrify the heating system. Do you have an estimate of what a typical cost would be to change from fossil fuel heating to electric heating per household?

Professor Cebon: I am not an expert in this area. Heat pumps are more expensive than gas boilers. There is some need to replace radiators in houses as well, although I have read a number of reports indicating that normal radiators work perfectly well with heat pumps in Victorian houses. Broadly, you are looking at a higher capital cost and a much lower running cost, which means that, after some period of time—perhaps five years—you get a payback where the lower running cost makes the whole system cheaper than using gas.

Professor Shah: Depending on the size, a heat pump could cost £12,000 to £15,000, which is why it may be worth spending a lot more money to improve the thermal performance of the house before you install the heat pump. You may need to make the radiators bigger, as mentioned. So it will be more expensive than a gas boiler.

The question is how that plays out over time in the savings made. A hybrid system of a very small boiler and a primarily electrical system could keep the cost down and find the right balance, not only because of the house but because of the back-end electrical infrastructure. You do not want a lot of power generation plant that is only being used for two or three months a year. You may find that the hybrid system balances the cost best. It depends partly on how people feel about paying up front and getting the savings over time versus paying for something that is cheaper but more expensive to run. There may be some policy interventions that can help with that.

Q20 **Alan Brown:** Professor Shah referred to policy interventions. There is a balance of paying for the heat pumps and energy efficiency, but, if we electrify, we need a greater amount of renewable electricity generation, which, at the moment, goes directly on to consumer bills through the CfD process. What would that look like for consumer bills in terms of an increased CfD mechanism and if they had to pay for the heat pumps and upgrades through that as well?

Professor Shah: If it is directly on the consumer, the up-front bit is the biggest thing they would see because a lump sum is paid on installation. The feedthrough is probably not as big as you think. The bill is already about 50% of non-wholesale energy costs. It is all the infrastructure cost. The renewable energy costs are coming down, so we would not see such a big proportion of the CfD part coming on to the bill compared to the infrastructure part, because that is the bit that has been growing a lot. It would probably have a modest effect on the bill side. The up-front bit of preparing your home and then installing the heat pump is where people would certainly need help. My son has installed one, so I have a bit of experience of how it is done now.

Q21 **Alan Brown:** Professor Cebon, the Committee on Climate Change has estimated 900,000 heat pump installations per year by 2028. At the moment, the UK Government have a target of 600,000; 900,000 pumps installed per year is 18,000 completions per week; clearly, 600,000 is 12,000 completions per week. How realistic is that from where we are at the moment?

Professor Cebon: We should not underestimate how enormous the task is. It is a huge task. I am not an expert on the construction industry. It is clear that, in new builds, we should just be putting in heat pumps. That is the obvious thing to do. It will be a slightly different cost but no more burdensome than putting in a gas boiler. All that new build should have heat pumps straightaway. The problem is the retrofit of heat pumps. It is a massive job. There is no denying that. People will have to be helped somehow. I am not really qualified to say whether it is practical to do the numbers that you talk about.

Q22 **Alexander Stafford:** Professor Cebon, I think it is fair to say that you are a hydrogen sceptic. I sit on the BEIS Select Committee, and we hear countless evidence from various businesses, charities and organisations that hydrogen is an essential part of the mix and is one of the many solutions for how we get to that. Your evidence today really does not tally with that. Are you right?

Professor Cebon: I am sure they are all right, but what they will find as we go forward is that the economics will dictate what happens. At the point when people have to buy new trucks, for example—which is the area that I work in—they will compare the cost of a hydrogen fuel cell vehicle and the cost of an electric vehicle. They will find that the electric vehicle is so much cheaper to buy and to run that they will make that decision by themselves. The decisions will be made by the economics.

The economics, as I said at the start, comes directly from the energy efficiency. If you have an efficient system, it has low costs to run. We have done that comparison for electric versus hydrogen-powered vehicles. We see that, because of the efficiency gains of electric vehicles, you can build a system where the freight operators can get their payback on the vehicle costs in a year and a half using an electric vehicle compared to a diesel vehicle, where the infrastructure provider can get a payback in 15 years with full tax recovery by Her Majesty's Treasury. That can happen because of the much lower energy cost of running those vehicles. It is perfectly possible to do it.

On the other side, you could buy a hydrogen vehicle that would be more familiar, because you would be able to fill it up and get a longer range and so on, but you end up not being able to do that without a very substantial subsidy on the vehicle cost from the Government in order to persuade people to switch from diesel and with a massive subsidy on the cost of hydrogen. The fuel costs to run those vehicles are three and a half times higher. Three and a half times more energy is needed to run the hydrogen vehicles than the electric vehicles.

The economics of this will work out by itself. The problem is that there is a lot of delay and confusion going on. It will take time for people to realise that the economics will talk, and, in that time, we are really wasting very valuable time when we could be decarbonising. There is a great danger of confusion and delay pushing decisions out five or 10 years. Let us just wait until the hydrogen price or the cost of fuel cells comes down a bit more. We wait and we wait, but we cannot afford to do that. If we are going to hit anything like the 1.5 °C global warming target, we need to massively decarbonise immediately. We cannot wait for hydrogen to get us numbers in a straight line, because it never will. The fundamental inefficiencies mean that it is far more expensive than electrification.

Q23 **Alexander Stafford:** If I understood you, it is about the economics. Would you say the Government have a duty to try to push things on? I would like both of your opinions on the hydrogen strategy, which we are hearing keeps getting delayed and delayed and delayed. It is now the end of the first half of this year. Would an intervention by the Government with an active hydrogen strategy kick-start this and help scale it up? For instance, as I am sure you know, the furthest north hydrogen refuelling station is in Rotherham, next to me, so it is not very far north at all. We do not have the economics of scale. How do you want the Government to approach the hydrogen strategy in light of what you have said about the economics of scale? I am keen to hear from both of you.

Professor Shah: The really important thing about hydrogen is that you need to get all aspects of the system up and running in one go. There is no point subsidising someone to produce hydrogen if there is nobody to transport, store or use it. You want to establish some value chains and some use cases that get some ecosystems up and running. The two use cases to go for the 5 GW for 2030 would be industrial decarbonisation at some of our industrial hubs and to find a balance of capital grant and CfD to supply hydrogen on a basis that allows people to decarbonise some of the major industrial processes that they run. That is something that can be up and running quickly, and it has a use case for producing, storing, transporting and using hydrogen.

The second one is to look at some of the more demanding transport applications and to work through the economics. I should make a couple of points about efficiency. Today's energy system relies on convenient technologies and convenient fuels, and it is economic, but it is not efficient. Internal combustion vehicles run at 30%, and thermal power plants run at somewhere between 35% to 50%. We have grown up with a system where we have not only prioritised efficiency but these other aspects. The hydrogen will play a role in areas where the efficiency is not the only consideration but there are other considerations of convenience, hence these two use cases that are places where you can get up and running. That reduces the uncertainty, and it clarifies some of the issues that have been raised.

In the demanding transport applications, vehicle utilisation can be a factor when we talk to people, which is why certain users would like to use hydrogen, because the vehicle is being used for its economic purpose and does not need to be charged too much. There are some cases where hybridisation makes sense, but probably in the bulk of cases electrification makes sense.

Professor Cebon: I would say two things to the Government. First of all, beware of grey hydrogen. If you promote a hydrogen economy and you do not get green hydrogen in place, and you do not get the carbon taxes in place, grey hydrogen will fill the gap. It is much cheaper than blue or green. The problem with grey hydrogen is that, if you replace natural gas with grey hydrogen, or diesel vehicles with grey hydrogen, for heating or for vehicles, the carbon emissions are significantly higher—much higher, actually. They are a factor of two higher between a diesel vehicle and a grey hydrogen-powered vehicle, with twice as high carbon emissions. Sorry, for home heating it is a factor of two. It is 40% for vehicles.

Beware of grey hydrogen because it will make things a lot worse. Do not set up a system where grey hydrogen steps in. You have done all this work to put in place the hydrogen-powered vehicles and the hydrogen-powered boilers. Now, we just need some hydrogen. So what do we do? We will use grey because it is the cheapest. That would be a serious mistake, which would dramatically increase carbon emissions from the country. That would be a mistake.

Secondly, if you want to go for hydrogen, be willing to subsidise for a very long time into the future. Be willing to spend a substantial part of the national economy on subsidising fuel prices for vehicles and for heating and buildings.

Thirdly, Professor Shah has pointed out that we live in a low-efficiency system. I would point out that diesel trucks are 45% efficient, not 30% efficient, but that is another matter. We are in a situation at the moment where, if you need more energy, you just put a bit more fuel in the tank. The diesel tank and the petrol tank contain so much energy that, if you need a bit more range, you just put a bit more in the tank. That is not the case in the new, future economy.

If you want more electricity, you have to build more wind turbines, more solar panels or more nuclear power stations. If you want six times more electricity for heating homes, instead of using heat pumps, if you need that factor of six, you have to build six times more offshore wind turbines and six times more electrification infrastructure. You cannot just put a bit more in the tank. We have been able to live in a situation where low efficiency was vaguely acceptable because we just burned more stuff. We are not in that situation now. We are in a much more difficult situation, where you have to build electrification infrastructure if you want more energy. That is why energy efficiency is so much more important now than it was before. We do not have the option to just "fill 'er up".

Q24 **Aaron Bell:** Thank you to both the witnesses for your time today. I would like to talk a little bit more about managing the uncertainty that you both talked about and also the optimum technologies that we ought to be looking at. First, you both said that we need to get on with it. Is any further evidence needed at this stage to resolve some of these uncertainties in the optimal role for hydrogen in achieving net zero? Starting with Professor Shah, do we need more evidence?

Professor Shah: We need to do the deployment phase rather than the innovation phase. In terms of hydrogen generally, the technologies that we have are ready. On the reforming, coming back to the point about the carbon emissions, in terms of very low carbon and capturing the process, I was talking about a leading UK technology from Johnson Matthey called the autothermal reformer with gas heating, which will capture somewhere between 95% to 97% of the carbon dioxide emissions. That is one area where it would be good to deploy it at scale and see how it works in practice. Although it is being used as a technology in methanol production, they are not storing the carbon dioxide. The steam methane reformer would not be the way to go. You would go for this more advanced reformer.

If we are going down a blue hydrogen pathway, it would be good to invest in that technology and get it working in the UK. As I say, it is something that is being used abroad. The big issue around blue hydrogen is the carbon capture and storage. That is a bigger thing beyond hydrogen. That is another aspect of Government energy policy and industrial policy that would need to be advanced quickly. Those would be the two areas where there is a lot of value in de-risking and developing. If we are going to have a low carbon industry in the UK, we will need some degree of carbon capture and storage.

Q25 **Aaron Bell:** Professor Shah, you have previously said that we should be finding niches for the UK to excel in rather than tackling the most difficult issues first. Are those issues that the UK could specialise in?

Professor Shah: Yes. The two niches I would look at are, first of all, blue hydrogen for industrial decarbonisation, which also has a geographical focus. It has a nice fit with some of the wider Government agendas around levelling up. The second one would be in green hydrogen for more demanding transport applications, building on UK technology. It will provide the kind of evidence and refine the economic information and data. It also allows growing out from those niches by expanding the use cases and the scale of production.

Q26 **Aaron Bell:** Professor Cebon, first, there is the original question as to whether we need further evidence, but, secondly, do you concur with those as niches that the UK could be looking at?

Professor Cebon: Yes, they could be. We could look at those things. I have mentioned before some aspects of that. How we are going to deal with ships and planes is a big question. The maritime industry seems to be going for ammonia. Ammonia is worse than hydrogen in terms of efficiency. You start with hydrogen. Then you add more energy to make ammonia, and then you add more energy to turn it back to hydrogen, so it is worse. That is an issue. Aircraft are a big issue. How those two are handled is very important.

My feeling is that there is a lot of biofuel available, and that should be the first place we look. We should take biofuel out of land transport and electrify it—there is a lot of it—and it should all go to ships and planes first, and then aircraft will have to use e-fuels. The idea of using hydrogen in aircraft is pretty unlikely and very difficult because of the vast volume you have to carry and the amount of the aircraft that you take up carrying hydrogen and the weight of hydrogen storage. That is very difficult.

The other thing is the technology readiness. Airbus says it might have a hydrogen-powered aircraft by 2035. Aircraft have an average lifetime of 30-plus years. If you start in 2035, at absolute best, you will have half of aircraft.

Q27 **Aaron Bell:** That is understood, Professor. Your written evidence to this Committee, which we thank you for, spoke of the need for the Government to pick technology winners. From a policy perspective, what does that mean? Is that literally what you have just said and the recommendations you have just made, or is there a policy framework they need to put in place in order to pick technology winners?

Professor Cebon: That is a very good question. First, there is a time imperative here. If we are going to get the job done by 2040 or 2045 to get the level of take-up needed by 2050, we are talking about massive infrastructure investment, probably over 15 years from 2025-40. In my area, in the truck area, we have done calculations on that, and we believe that is possible. That means we need clear signals from Government by 2025-26 or something like that. If you need 15 years for building infrastructure, there is a short window available now.

My opinion is that we should be able to pick technologies that will pay for themselves, where you do not have to have massive Government subsidies, and electrification is one of those. However, to pay for itself in the long term, you need some guarantees of stability in the market. Companies will not invest in long-term infrastructure projects if they do not have some guarantee that there will be appropriate support from Government. That is a very important thing.

The other important thing that is really critical is the way these decisions are made. There are a lot of special interest groups and a lot of lobbying. There is a lot of incumbency. It is very important that you have an impartial and objective assessment done by independent people, because those decisions will affect the economics of the nation. You cannot afford to have those decisions made by incumbent interests or being lobbied by incumbent interests. It is very important to get that framework straight so that you get good decision making in place.

Q28 **Aaron Bell:** Thank you, Professor. Unlike some countries, the UK Government have indicated they are going to pursue both blue and green hydrogen. Professor Shah, is that the right decision for the UK Government, and what factors will be important in determining the appropriate balance between the two?

Professor Shah: For countries like the UK that have carbon storage, it is exactly the right strategy because you can get a hydrogen ecosystem operating at a cost level that is not too demanding for the early applications. It gets up to scale very quickly. As I say, there are known technologies like the JM technology that can be deployed. If we look at 5 GW by 2030, it is only achievable through a blue hydrogen strategy.

For Australia, the UK, Norway and the Netherlands, you can see that this mixed strategy makes enormous sense. For Germany and France, it is more difficult for them because they do not have access to carbon dioxide storage, so they are going primarily with green hydrogen. It will take them quite a lot longer to get to scale, to get those value chains up and running. For industrial use, you need large amounts of hydrogen at a price point that is not £6 per kilogram at the moment. The green costs will come down with renewable energy cost reductions and technology improvements, but we do not have that luxury in terms of the timing. The twin-track strategy of the UK is exactly the right strategy.

Q29 **Aaron Bell:** Professor Cebon, do you have a brief comment on that? We are over time already.

Professor Cebon: We need electrification wherever it is possible and hydrogen only to fill the places that electricity cannot meet.

Aaron Bell: Thank you; that is very clear.

Q30 **Chair:** I have two brief, final questions. Professor Shah, you mentioned that the lack of take-up of hydrogen would be solved if the true costs of energy were reflected in the system. I assume you mean the costs of carbon. Professor Dieter Helm made a proposal that we should have a universal carbon price across the economy and then technologies would respond according to how they fit with that. Does that conform with your view as to what should happen?

Professor Shah: It is probably the simplest way to get this up and running. The reason is that it would start in places where you can make interventions relatively easily. A good example would be in industrial decarbonisation, where we looked at exactly that question around industrial clusters. You find that, at certain price points, you see investments in hydrogen use as a fuel, in carbon capture and storage as a way of capturing industrial emissions, and indeed in increased use of electricity for certain aspects of industrial processes. As you increase that carbon price, you can drive a whole industrial cluster to net zero, and the technologies are available and the investments are possible. That is because, with an industrial process, there tend to be a few single payers for energy who see it on the bottom line. When that is distributed more broadly across the economy to each of us as individuals, we may choose just to pay the price and not to make those investments.

It becomes more complicated when you are dealing with millions of people having to make individual choices. There are places like industrial clusters where it will work well, with big transport fleets, where there is a rational person doing a cost-benefit analysis. Unfortunately, as individuals, we do not tend to work on that basis, and it will become more muddied.

Q31 **Chair:** Thank you very much for that. Finally, Professor Cebon, you have been very eloquent about the efficiencies of the process of using hydrogen. In those circumstances in which we have renewable energy installed beyond the reliable capacity that we need—in other words, we have capacity there for peaks of demand, but there are times when it is not used—is that an efficient use to make of wind power when there is not enough use for it across the economy? Is it reasonable to use that to create hydrogen?

Professor Cebon: No. There are much more efficient ways to store that electricity. There are two things you can do under those circumstances: you can curtail it and you can dump it—that is not a completely crazy thing to do—or you can store it. If you are going to store it, then you want to store it in a way that is going to give you the most possible electricity back again. As I started off by saying, if you store it by hydrogen, you get 30% of it back again. If you store it by other methods—and there are a whole variety of other methods with round-trip efficiencies typically of 70% or more—then you get 70% of it back. You can sell that 70% rather than only having 30% to sell back to the grid. It is economically much more attractive. The levelised cost of storage of those systems is lower than hydrogen as well.

Hydrogen seems like the answer to everything—the silver bullet—but it is not better for trucks, it is not better for home heating, and it is not better for storage. There are alternative electrical options that are better in all of those three cases.

Chair: Thank you very much. We will go in detail in these sessions through some of those uses. Your point about it not being the most efficient means to store electricity is very helpful. It has been a fascinating hour. It has really brought to life some of the big choices and indeed some of the controversies around this area of policy, and we are very grateful to have had your expertise this morning. Thank you very much indeed for joining us and thank you, as my colleague said, for your written evidence as well.

Examination of witnesses

Witnesses: Michael Liebreich and Dr Baxter.

Q32 **Chair:** We now welcome our second pair of witnesses, whom I am delighted to see on the line. They are Dr Jenifer Baxter, who is the chief engineer at the Institution of Mechanical Engineers, and Michael Liebreich, who is the founder of Bloomberg New Energy Finance and a visiting professor at Imperial College's Energy Futures Lab. Welcome to both of you and thank you for joining us.

I will start with a general question to you both, first to Dr Baxter. What do you see as the prospects of hydrogen in supplying our energy needs during the period to 2050?

Dr Baxter: It is really important at this point to note what we are trying to achieve, and that is primarily the displacement of fossil fuels from our energy system, the reduction of emissions to atmosphere and better air quality. Hydrogen plays a part in this and getting towards net zero and improving our environment. That comes in a number of different areas.

You can think about what we do currently and where hydrogen is used now, which is primarily in industry. We use it in the petrochemical industry, the manufacturing industry and the fertiliser industry. About 52% of hydrogen produced today is used in the production of ammonia. That is all using either grey or brown hydrogen, which is effectively dirty hydrogen. In the first instance, that is the area where the type of hydrogen we use needs to change. From that, from the development of that new infrastructure that supports those industries, you can begin to see options that are further than industry, within transport, potentially within storage of electricity, and wider than that, where hydrogen can become a really important part of the future energy system.

Q33 **Chair:** Thank you. Michael Liebreich, I do not know whether you heard some of the last session. There were conflicting views there. You have written extensively about it. What do you make of the current debate about the potential for hydrogen in getting to net zero?

Michael Liebreich: Good morning. It is good to see you, Greg, and thanks for having me as a witness today. Unfortunately, I was not able to join the last session, but I am very familiar with Professor Cebon's work. Broadly, whatever he said I probably agree with. I do not know how many of you might remember the Heineken slogan from the 1970s and 1980s, which was, "Heineken refreshes the parts that other beers cannot reach." Hydrogen decarbonises the parts that direct electrification does not reach. It will be essential, as Dr Baxter said, to replace the dirty hydrogen used in petrochemicals and fertiliser production with clean hydrogen, however we get that. That is absolutely clear.

Going beyond that, you can see uses for it, but when you dive into the economics, they are the ones that direct electrification plus batteries cannot reach. They look like things like, potentially, steel, shipping and aviation, and they may look like deep resilience on our grid, on which I am very concerned that we all focus, whether in this session or just in general.

When it comes to heating, the inherent efficiency is devastating compared to heat pumps. When it comes to transport, the inherent efficiency and also the sheer complexity of the vehicle compared to the sheer simplicity of the electric vehicle is a showstopper. There might be niches in transportation. You could have a good discussion about long-distance trucking. If you want to go on a road-train across frozen Canada, then you might find that hard electrically, and you might look for another solution, but for most of the things that we are familiar with, even up to heavy trucks and long distance, it is unclear why you would go to this inefficient, complex solution when cheaper and simpler ones exist or are coming to market as we speak.

Q34 **Chair:** Thank you, Michael. Dr Baxter, as the chief engineer of the

Institution of Mechanical Engineers, would you give your perspective on this key question of efficiency that we heard so much about in the previous session? Is it the case that the use of hydrogen is fundamentally inefficient compared to its alternatives? If you think that is the case, do you see that as being a constraint on its use?

Dr Baxter: It will always be a challenge when you have to extract your energy vector from another set of components. For example, if you have to take something from water, or you have to take something from methane, there is a process that you have to go through to do that. There is an added amount of energy that is required. The question becomes: efficient in comparison to what? Professor Shah mentioned the fact that the current energy system, which we are mainly reliant on, which is fossil fuels, is inefficient. For example, if you imagine, just easily, a piece of coal, you get about 30% of the energy from that as it goes through the thermal power generation process. With gas, possibly you might get up to 50%, but none of these processes is efficient.

We are having a slightly binary discussion on whether it is hydrogen or electrification, and, actually, those are not the questions. The questions are: what is the wider energy system that we are currently using, and which parts of it do we need to change? It really is the majority: over 90% of the energy system needs to be changed. Electrification at the moment, and our renewables, are still a small part of the overall energy system. Electricity is about 16% overall, and last year renewables were producing just over 50%. So it is still a very small amount.

We have to ask the question: compared to what? It is not just electricity. It is much wider—about which fossil fuels we are using, what the fugitive emissions are, for example, from the extraction of those fuels from the ground, and the role that hydrogen can play in displacing some of those.

Q35 **Chair:** Before I go to my colleagues, on the question of the different modes of generating hydrogen for use—grey, blue, and green—what are the prospects for each of those in the future for the UK, Dr Baxter?

Dr Baxter: We already have hydrogen produced through steam methane reforming, and that primarily happens on industrial sites. Often, blue hydrogen is talked about because it is an easily understood process where you can add carbon capture and storage to it. There is a reality check on whether we want to be bound to a fossil fuel system in the future and whether that is the right thing to do as a transition to a much greener hydrogen or potentially hydrogen produced from nuclear power stations in the future, and we have to ask ourselves if that is what we want to do.

I suggest that it is much better to look at the possibilities for the generation of green hydrogen or using, potentially, biomethane for some form of autothermal reforming as well, with carbon capture and storage or use of that carbon dioxide in another way. That means that you can start to bring together industries in much more symbiotic relationships, where you can support farming within industry, for example. There are all sorts of different ways we can do it. Often, we focus too much on the very blunt instruments that we see in front of us, when engineering can be much more creative and we can start to bring together our industries to work more to reduce emissions.

Chair: Thank you very much. I am going to my colleagues now.

Q36 **Alexander Stafford:** Thank you for this evidence. Touching on the blue/green hydrogen situation now, should there be a time limit on blue hydrogen? It is clear that the Government want us to get to green hydrogen, and green hydrogen is going to be the ultimate solution when it comes to hydrogen. Should we put a time limit on the phase-out already of the use of blue hydrogen, or should blue hydrogen always continue?

Dr Baxter: That is an interesting question because we do not really produce any blue hydrogen at the moment, so putting a time limit on it is a bit of a challenge. Certainly, my gut feeling is that we want to be moving away from basing our energy system on fossil fuels. That means that there has to be a limitation to how long you do that for, because it will ultimately probably be cheaper in the short term to produce blue hydrogen than to produce green. The subsidy of support from Government should perhaps be focused on green hydrogen, or "renewable hydrogen production" might be a better term. I think the colours are somewhat confusing. That might be where we focus our attention.

Q37 **Alexander Stafford:** I am keen to hear Michael's views as well on the timescale.

Michael Liebreich: The answer is no, not the timescale. The colours are a nice, easy gateway drug into the hydrogen discussion, but the problem with them is that they are simplistic. At the end of the day, hydrogen is just a molecule. The question is: why do people not like blue hydrogen? There are basically two good reasons and one bad reason. The first reason is fugitive emissions because, if it is natural gas, then you worry about how much of it is escaping in the supply chain. That is a good thing to worry about. The second thing you worry about is the capture percentage, because, if you only capture 90% of the carbon, there is the 10% and you have to do something about that. Both of those are problems that will yield to research investment.

This is not like the fundamental thermodynamic problem of electrolysing to get hydrogen or converting hydrogen back into electricity. These are things that you can invest against, and there are approaches to get nearly 100% carbon dioxide capture while making blue hydrogen—to use the colours—and also the fugitive emissions. There are operators that have much better records on fugitive emissions, and ones that are much worse. So what we ought to be doing is worrying about those.

The third reason why people do not like blue hydrogen is because it involves oil and gas companies, whom they hate for some good reasons historically, such as their bad behaviour, and some less legitimate reasons, let’s say. We will not be able to decarbonise the global economy and the UK economy without working with the oil and gas companies.

With any form of hydrogen, when it comes to the companies that have the experience of moving around large amounts of fuel—gases and so on—that is what we are talking about: the oil and gas companies. We have industries like cement that produce CO_2 that we will have to sequester. You will have to do that with the oil and gas companies and their supply chain. That third reason, “Oh, we don’t like oil and gas companies,” is not legitimate, in my view. What we should be doing is focusing on standards for hydrogen production, and good luck to anybody who can meet them.

The other thing we have to remember is that every kilo of renewable hydrogen that we produce has a footprint or casts a shadow in terms of the land use, the offshore resource use, or the area use, that we need to add to the system. It is not like the renewable is totally clean and wonderful and the blue hydrogen is somehow tainted and evil. It is not as simple as that.

Q38 **Alexander Stafford:** Can I just pick up on one thing, Chair? It is a matter of interest. I used to work for Shell prior to being elected. I want to pick up on the point that Michael has just made about oil and gas companies and their position in this. On your evidence, Michael, do you think that oil and gas companies should be involved in producing hydrogen and getting behind the network, or should they not be involved in this?

Michael Liebreich: Responding in the same spirit, I am an adviser to Equinor. I am on their international advisory group, and I was for a little while an adviser to Shell as well. Yes, I do. It is not that I think that because I am an adviser. I am perfectly happy to work with those companies if they are in good faith. I think that is key, and there is a value judgment around that. There is a lot of talk going around and a lot of net zero targets, et cetera, et cetera. If those companies are in good faith about supporting the net zero 2050 targets of the UK Government and the Paris agreement, you absolutely cannot do an end run around them. You have to bring them in and work with them.

Q39 **Alan Brown:** Michael, the UK Government plan to have two carbon capture clusters up and running by 2025. How realistic is that aspiration? Also, in the wider sense, can you estimate how well placed the UK is to be able to benefit economically from hydrogen compared to other competitors?

Michael Liebreich: With regard to 2025 for the carbon capture clusters, I cannot see any reason why not. This is not splitting the atom, as back in the day. The technologies and the components exist to do this.

Certainly, at a pilot scale, getting-started scale, to deliver major industrial projects in four years is not impossible but probably quite a stretch. How well is the UK positioned? The answer is incredibly well, because we have the North sea, we have an oil industry, we have the City of London, and we have a fabulous science base. Are we ahead of others? I cannot think of anybody ahead of us.

If you look at retail use of hydrogen in cars, you would immediately go to Japan. Since that is a foolish thing to do, I do not really put much weight on that. There is, however, a race on around hydrogen clusters or hydrogen hubs. I like to call them hubs because I can then distinguish it from homesteads. Anybody who wants to get a few houses off-grid and so on, that is all foolery and not a big deal. Hubs is industrial. What we have going in the Humber and Teesside, those sorts of things, is the race, and we are absolutely well positioned and must not squander it.

Q40 **Alan Brown:** What needs to be done to stay ahead in that race after winning the race then?

Michael Liebreich: That is a great question. It would be helpful to focus on the uses of hydrogen that make sense. Focus on industry. In other words, focus on the hubs, and do not get diffused around some of the applications that I just don't think ultimately will work. It is hard to critique.

Obviously, there has to be some money. There has to be some co-ordination. I do not want to go as far as to say central planning. I do not want to be too controversial, but there is this, "Hydrogen works for so many things; therefore we just jump to a hydrogen economy." That is not how it works. What happens is that hydrogen on the demand side has to win every battle and every niche against the other alternatives, not against coal. We all know we are getting rid of coal. That is not a big deal. Hydrogen needs to beat direct electrification if it wants to win. We need to focus in on those things. I do not think we should be nationalising the whole effort. It is a question of bringing stakeholders together.

Q41 **Alan Brown:** Dr Baxter, do you have anything to add? Is there a greater economic opportunity in electrification?

Dr Baxter: This comes down to a little bit about where you are in the country as well. I should also declare that I am a director of innovation and policy at Protium Green Solutions, which is a hydrogen development company. We are in the process of implementing some of these activities on the ground. You often see that it really is dependent on what resources are available to you in your industry dependent on where you are in the country. For a lot of people, electrification, at the moment, is not a solution, and they do need to find a way to decarbonise their industries. Those are particular industries that are often storing some form of fossil fuel on site for use in their processes, where hydrogen becomes a real option and something that they can both produce and use on their site, and then they can also use it for the distribution of their products.

There is an opportunity in terms of direct subsidy support in some of these to allow companies to transfer away from fossil fuel in the short term, which will have a big impact on reducing emissions in the UK from industry. There is some opportunity there, and with that comes the skills base, the supply chain development, which we have missed out on in previous industries—for example, wind in the past, where we have not really gone for it in the same way. There are some real opportunities in that sense when you start with the smaller areas and, as Michael has said, hubs and clustering. They are a really good place to start to build up some of these skills.

Chair: Let us move to Philip Dunne, and then Mark Logan and Rebecca Long Bailey. You are muted, Philip.

Philip Dunne: It said I was muted by the Chair, but thank you very much, Chair.

Chair: Not guilty.

Q42 **Philip Dunne:** I should declare that I am a director of Reaction Engines, which is a member of the Jet Zero Council looking at early-stage technologies for hydrogen use in aviation. I will ask Michael Liebreich my first question. The Government have delayed the production of their hydrogen strategy pending the Energy White Paper, which is now out, and we heard earlier that they are due to publish in the second quarter, having previously been planning to publish in the first quarter this year.

Can you give any recommendations to Government as to where this strategy should focus, and in particular—we have just heard both of you talking about clusters, which appears to be the direction of travel in the 10-point plan—will that be enough to give enough structure and demand signal for the industry to be able to invest?

Michael Liebreich: Let me see what I can do. It is almost a qualification of my last answer, which said, "Bring the stakeholders together, and focus on those clusters and the industrial uses." One thing we have to be clear about, though, is that hydrogen is not now economic. We have an economic gap. If you were to say that the first thing we should do is get hydrogen into fertiliser and refineries, then you have to deal with the fact that, whether it is blue hydrogen or green hydrogen, there is a cost problem. Green hydrogen currently probably costs around $3.5 per kilo against $1 or $1.5 market price. Blue hydrogen may be a little bit cheaper; it may be $2.5, but there is a delta. That would be a first place that you have to look to say, "If we want any of this to happen, somebody is going to have to close that gap."

Over time, the experience curve will do wonderful things, but we are where we are. You have to get that pump-primed and running. You have to close that gap. I would be looking for some approach to that. There are different ways that you can do it, but that gap needs to be closed.

The other piece is on the demand side. To get the supply side up and running, you will have to help them close that gap. That will produce low-carbon hydrogen, but then the question is where you want it to go. That might well get it going into fertiliser and petrochemicals, but the moment you want to get it into aviation, your pet subject—it might be e-fuels; it might be hydrogen—or you want to get it into shipping, maybe via ammonia and so on, those solutions are more expensive than hydrogen. They are not using grey hydrogen today. They are using even cheaper natural gas, diesel or whatever. There is another cost gap that you have if you want to start working at getting the markets there on the demand side.

I would be looking for a selection on the demand side of places that make sense, not wasting money, but then helping to close those cost gaps and trying to get those experience curves working. However, you will have to do something economically to close the gaps, supply-side and demand-side.

Q43 **Philip Dunne:** Pursuing that, the Australians have the mantra of getting the price down to 2 Australian dollars for H_2—2 Australian dollars for a kilo of hydrogen. Their current price is about 6 Australian dollars, I believe. That is not stopping them from investing very significantly at a Government level in looking for support. Do you see parallels, as we are regularly told, in the way in which the offshore wind sector, by investment, got the cost of production down so significantly?

Michael Liebreich: Very definitely, yes. If you use a number of 6 Australian dollars, that would be if you use a small electrolyser right now. It is that sort of boutique scale. I have already been talking to people doing mega-projects in Australia that could break ground as soon as they got the final investment decision and produce for about 3 Australian dollars. It is the same in north Africa and the Gulf: 3 Australian dollars for green hydrogen right now, but that is still a way off. The target really wants to be $1, which is a bit below 2 Australian dollars. It is something like 1.5 Australian dollars or 1.6 Australian dollars. I do not know the exchange rate right now. We will get there. The electrolyser costs will come down. The renewable energy costs will come down, and we will get there.

The problem you have competing with Australia is that they have solar power. If they built very substantially—it is the same in Morocco, the Gulf, Chile, in parts of India and China—they could get solar power for less than $20 a megawatt-hour, which is £15 a megawatt-hour. The problem we have with our major renewable resource being offshore wind is that, even with the best of horizons, it will probably still be $30 or $40 per megawatt-hour even in a couple of decades.

We have to be very careful not to compete, or to figure out how we are going to win, against what I call these renewable energy superpowers where you get both wind and solar for very low cost—$20 a megawatt-hour or below—and you can put them together and get high-capacity factors, run your electrolysers cheaply. That has to be the way to go. If you are just after the cheapest hydrogen or ammonia possible, it will be very hard to compete in global markets out of North sea wind.

Q44 **Philip Dunne:** Dr Baxter, could I ask you a similar question? We understand that there is considerable scepticism in the Treasury about the role for hydrogen. What evidence is needed to enable the Treasury to be persuaded that this is a technology that needs to be supported?

Dr Baxter: We know that, already, there is significant investment, that is well ahead of previous predictions, into hydrogen that is happening across the globe. There was a recent report by the Hydrogen Council that showed that we were probably about five years ahead in terms of investment into hydrogen projects globally. This is not just solely in the UK. That gives us a real insight into the interest that there is and the opportunities that hydrogen presents to us to get to real levels of decarbonisation. We still have very large challenges ahead of us in terms of electrification and our transport system. We have not talked so much today about the scale of what we are trying to deliver and where we are trying to deliver it, but it cannot be underestimated at all.

You spoke a little bit about aircraft. I work on the Future Flight Challenge with Innovate UK, and there is a real interest in the role that hydrogen can play, particularly in small aircraft. We have not talked today about performance. So, yes, you can electrify all sorts of things, but their performance is not as good as if you use something with more energy density in the fuel. We have to start to consider what is the best solution. Electrification will work for lots of things, but it really will not work for everything, so we have to use other sources of decarbonisation. We have talked a little bit about demand reduction, but probably not enough. That is really the place where we have to reduce demand across all of our fuel uses.

Q45 **Philip Dunne:** In relation to both transport and home heating, where we have heard considerable scepticism today about the role for hydrogen other than at a niche level, can the Government adopt a technology-neutral approach for long, or will they need to pick one or the other either for transport or for heating?

Dr Baxter: From my point of view, I am not sure that it is a sensible option to pick winners, because you then limit yourself to what options innovation may bring forward. All technologies will develop if they are invested in, whether that is electric or hydrogen vehicles. They offer different solutions to different end users. We cannot imagine that everybody has the same need for their vehicles. We have to make sure that we are presenting those different options.

Q46 **Philip Dunne:** Michael, what is your view on picking winners and technology neutrality?

Michael Liebreich: I differ. I would like to come back on the point about small aircraft. The fact is that an electric aircraft outperforms the current fossil fuels small aircraft, because they have better torque and they are quieter. They can take off from shorter runways, and you could use your smaller airports later in the evening and open them earlier in the morning. Obviously, they do not have the range. For longer range, we will need liquid fuels or hydrogen. There is a role there.

My heart sinks when I hear words like the Hydrogen Council. The Hydrogen Council is a bunch of very large companies that want hydrogen at all costs, and they do not give a damn whether it is the most efficient solution or not the most efficient, or the cheapest or not the cheapest. They are well funded to produce research and do all this stuff.

The fact is we will have to choose some winners. If we want to have electric trucking in the UK, there are infrastructure and planning questions. There are major investments by other major companies that will have to be made. At some point, we have to stop the mantra of all technology might improve, when the fact is that some of them have just got thermodynamic and microeconomic challenges. A hydrogen truck compared to an electric truck is a completely different beast. It is not correct to say, "We did it in solar, we did it in wind, and, therefore, we can do it in everything." Electrolysers will become much cheaper—experience curve—but producing hydrogen from water will not become orders of magnitude more efficient. Fuel cells will not become orders of magnitude more efficient, in the same way that we are only getting 50% efficiency out of gas turbines after how many decades. In fact, a diesel engine in a truck is something like 15% or 20% efficiency in terms of the motive power at the road, and that is after 120 years of development. We have to be realistic here, and there are decisions.

On trucking, we will have to settle on some solutions with our European partners. With long-distance trucking, you have to have a solution for the trucks that come in that are going across the continent. We will have to choose not winners in terms of companies but architectures. We will have to make some decisions. There are some sensitive intervention points where we need to say, "This is probably going to work, and we need to back it," and, "This is definitely not going to work, and we definitely should not."

Then there are areas where you can be technology neutral—steel, for instance. Everybody has decided, "Hydrogen will work for steel," but it could be direct electrical reduction, which is also undergoing research and looks promising. We do not want to choose hydrogen for steel and choke off research into the direct electrical alternatives. In some areas, where we can say, "Look, we have had 30 years of trying this or that, and it has not worked," and the thermodynamics, microeconomics and the economics are not in its favour, we surely have got to move on.

Q47 **Mark Logan:** Some of my questions have actually been asked and/or answered, but could you expand a little more on the extent to which the Government can more effectively promote hydrogen development?

Dr Baxter: I will happily answer that. I need to come back very briefly on something that Michael said. It is the concept of treating everybody and every sector as if they need the same outcome, which they don't. There are parts of the UK where it will just not be possible to deliver a fixed pathway, so we have to be mindful of that.

This then builds on to the idea that people and communities will get left behind because investment into certain types of infrastructure will happen easily in some regions, and in other areas it will not. If we do not run some parallel programmes supporting more regions, you will just end up with more of the country left behind.

There are areas where certain things will work really well—electrification for cities, for example. That is an obvious one. New build housing we talked about a little bit earlier, where that should, 100%, be heat pumps and electrified, but it is just not feasible for a lot of the country at the moment. We need to make plans to support them and not make decisions based on our views about how everybody should live, when it is not possible to do that.

In terms of Government support, it is making sure that those parallel programmes run together and that we are able to ensure that each area of the UK for those of us who live in more remote areas is also getting the support to decarbonise as much as those who live in the city. For hydrogen, there is a slight difficulty with CfD, which people mentioned in the previous session, in that, because hydrogen can be used for multiple purposes, it is difficult to run a clean CfD auction. Direct subsidy may be more appropriate in certain areas. That will allow some of these projects to come online. The more projects that we have, the more black-boxing of innovation that we will see, and the more opportunities for supply chain and investment to build up around that. There are a variety of options that the Government could take. At the moment, the only subsidy for hydrogen comes under the renewable transport fuel obligation; there is not much else. There is an opportunity to look more widely at policy support for it.

Michael Liebreich: I agree that we definitely should not be pushing for one size fits all. That is a straw man. If you look at heating in remote communities, for instance, it may be difficult to electrify. Dr Baxter has mentioned another solution, which is probably under-represented in the debate overall, which would be biomass and biogas. We will have some volume of that that we can produce sustainably out into the long term. We have not maximised our production. We need to make sure that that is used to solve the problems. It is almost the Heineken solution: electrification and batteries where that can work, and, where it cannot, we should be looking at biomass and particularly biogas solutions. I am not saying, "Don't look at the hydrogen solutions." By all means look. I just think that you will look and find that it does not economically work, whereas it definitely works, we know, in fertiliser and petrochemicals, and perhaps in other areas. That is where we should be focusing.

I want to answer your question, but I also want to make sure that we do not run out of time to talk about deep resilience of the electrical system. That is another potential use for hydrogen because it can be stored in salt caverns large-scale. One thing that worries me about the "electrify everything" route, which I am very convinced is the right route, or electrify as much as possible, is that it makes us enormously dependent on the power supply for even more than we currently use it for. If you think about all police cars, all ambulances, home medicine, our supply chain, everything is becoming very closely connected, and we have just seen what happens in Texas when that falls over, or in California, or indeed in the UK last year.

We need to think much harder about deep resilience of our electrical system, and that comes back, to a certain extent, to the question of how Governments should support. I would agree with Dr Baxter on how you jump-start things and on weaknesses of this approach or that. I would like to see a lot more money going into R&D. I would like to see money going into Government procurement, making sure that the MOD and the NHS are given funds to help jump-start markets, because they can do that on a large scale.

However, there is also work to be done on the resilience of the electrical grid and, potentially, the use of hydrogen therein. I am talking about deep resilience, not just a little capacity market that helps get through some wobbles. I am talking about what happens if three of our interconnections are taken out by cyber or terrorists at once, or if there is a very unusual weather pattern, similar to what happened in Texas, or no wind or low wind for two or three weeks in the North sea. How do we get through that, and what is the role of Government and support? If we put hydrogen into salt caverns and keep it there, and it might not be used for five years, which company is going to do that? The markets will not supply the price signal without support from the Government.

Q48 **Mark Logan:** Briefly, Michael, and this is maybe more of a yes or no sort of question and answer, the Government appear to be focusing heavily on hydrogen for heating. We have heard some healthy scepticism on that in the first panel. Is that an appropriate short-term strategy?

Michael Liebreich: I am always very happy for a small amount of money to be spent, even if it is proving definitively that it is a stupid idea, but I think it is a stupid idea because of the inherent inefficiency. Why would you go to all the effort, generate the electricity, produce the hydrogen, and then simply combust it? It is being touted as a way to maintain the value of a gas distribution network rather than as a sensible solution doing the hard yards of thinking through net zero heating for homes, in my view.

Dr Baxter: To a certain extent I agree with Michael, but I think there is a little bit more to it than that. It is a bit more nuanced. One thing is around biogases and the amount of biogas that we have, where it comes from, and how much of that is put into the gas distribution system rather than straight methane. However, there is another side to this. If it is appropriate for a particular area to have a hydrogen grid, then, fine, but it is probably not appropriate for the whole of the UK to suddenly try to produce enough hydrogen to fill the heating system. There is a challenge in that 85% of all homes are on gas central heating. As we heard in the previous session, it is around £15,000 per home to replace, and if you live in a house like mine, neither an air source heat pump nor a ground source heat pump can be fitted here, so that means I do not have that option. You then have to think about what the other choices are. We have to be a bit more nuanced in our thinking. It is not that straightforward.

Q49 **Chair:** Picking up that point from Mark, Professor Cebon in the first session would say, I suspect, that the answer to the households that would not be able to have the energy in the way that you describe is to use electric central heating rather than change the boilers. Is that not the most direct solution?

Dr Baxter: To run electric heating for a large house?

Chair: Yes.

Dr Baxter: Potentially, it is quite costly compared to gas at the moment from that point of view. I only say that from my own experience. There is an ease in the way that the system works, and some of that will be reflected as well in heat pumps and air source heat pumps. I happen to have an air source heat pump in my tumble dryer, which has not worked for three months this year because it gets below the temperature, so I have to put it next to a radiator. That is a hybrid heating system, but not that one that we want. It is about making sure that options are available to different people. I do not live off grid. I live in a city, but I just do not have the space for the systems that I would like to put in.

Q50 **Rebecca Long Bailey:** Thank you, Michael, and Dr Baxter. I really appreciate the wealth of expertise you have both brought to the session today. Michael, it is becoming increasingly clear to the Committee that uncertainty surrounding the future of hydrogen has invariably restricted deployments based on market assumptions alone. What sustainable investment levels are most effective in ensuring roll-out at scale? For example, a number of submissions made to the Committee backed a contract for difference. Others have been suggested to the Department for BEIS, such as RAB—regulated asset base—and cap and floor models, and usage obligations for certain users.

Alternatively, should they be moving away from those revenue guarantee models toward a premium model where producers and customers might secure a better deal? For example, producers receive a subsidy on top of their market revenue, but the Government take a stake and also receive a proportion of revenue—a public/private partnership, if you like. It would be interesting to hear your thoughts on all of those models and any other alternatives we might not have thought of yet. It will probably take more than a session to cover it all, but if you can allude to your preferred option, that would be helpful.

Michael Liebreich: I have not gone through all of those options in great detail, and, if I had, it would take more time than we have available to deliver my verdict. The experience that we have had from renewable energy is that things go through different stages. Very early, when sectors are very small, it almost doesn't matter. You just want to get the activity going because, frankly, if it is wasteful, it is so small in the scale of Government budgets or energy spending that it is immaterial. What you need to do is to go to the individual stakeholders you want around the table doing stuff and pay them to do it, in a sense. That is very early stage R&D and pilot projects.

Once you start to get into the scale-up, very quickly you need price discovery, because the big mistakes that were made across Europe, Germany included, were these feed-in tariffs, where the thinking was, "Our bureaucrats are so clever that they could do what all of those brilliant Soviets could not do and figure out the price, and do central pricing." What happens is that industry game it, they force you to produce a price that is up there, and then miraculously they can do things and make rents.

That is why CfD is a good approach, because you recoup if the industry moves faster. You have to have the reverse auctions. You have to have price discovery and, of course, you have to have pay-for-performance. In other words, if somebody makes lots of steel using hydrogen, then you want them to be paid for that. Just getting a grant at vast hundreds of millions to do X, Y and Z, but never producing anything, should not qualify. There is pay-for-performance and price discovery. Those are more general rules that you could use as you look at different policy mechanisms. Does it incentivise rapid uptake, because that gets the volume, and does it force price discovery, because that gets the price competition, which we have seen is much faster than anybody would think or that industries would like to commit? It puts them under pressure. What do you want? It is good.

Q51 **Rebecca Long Bailey:** Thank you, Michael. Dr Baxter, you have a lot of on-the-ground experience. Do you have anything to add to Michael's comments? What would give you and your peers the confidence to invest now?

Dr Baxter: As I mentioned before, CfD is a challenge. With something like wind, it is straightforward. You produce the electricity and you put it into the grid. With hydrogen, it is slightly different because you can use it for multiple end users, so it depends on how the CfD is set up and whether you can make sure that you prevent any level of bias towards one type of industry or another with that. So there are options there.

On the ground, we are seeing that a lot of companies, because only the RTFO at the moment is supporting hydrogen, and a lot of people are looking at how they make hydrogen and then how they use it somehow in their transport fleet, because that is a way in which to make some money back. From that point of view, from offtake agreements, companies are trying to understand how it all combines together. There is not really any kind of support mechanism that supports industry changing to a different system. How can we build that into what we do in policy development?

Q52 **Graham Stringer:** I would like to develop a point you made previously—it is quite obvious, but it is a considerable one. We cannot have an infrastructure for hydrogen for long-distance trucks if the EU or the rest of Europe is running electric trucks with a different infrastructure. That is also true for aviation. You could not be running aeroplanes on hydrogen, or even on biofuels, to get to other parts of the world, and for shipping. I would like you to develop the point a little, but it is not essential.

Chair: There might have been a problem with the sound there.

Michael Liebreich: I heard it, but I do not know if it was addressed to me though.

Chair: Perhaps Graham would repeat the question. Can we test his microphone? Is that working now? Graham, repeat the question if you would not mind. The microphone was not picking it up.

Q53 **Graham Stringer:** Michael, I wanted you to expand on what I think is a very important point. We cannot decide—or pick winners, if you like—when it comes to what fuels to put into aeroplanes, what fuels to put into ships, what infrastructure to put in for long-distance lorries, if the rest of world is doing something else. We cannot have biofuels in planes if the rest of the world is running on hydrogen, or vice versa. Could you develop that point a little?

Michael Liebreich: There are these areas where there will be a convergence on a solution. With aviation, you could not possibly go it alone. On that, the UK is well positioned in terms of our role on the various international bodies, whether it is the IMO for marine or ICAO for aviation. There is a well-established process internationally that needs to come to a conclusion on those. What we need to do—and perhaps this is where it would fold into the activities around COP26 in Glasgow later this year—is give those processes whatever impetus we can. We will not solve some of our footprint domestically unless we also make progress—indeed, that would be a get-out-of-jail-free card for the global economy if we do not move fast. There is a lot going on there. We need to co-ordinate with our international partners.

Long-distance trucking is an interesting one because it turns out that it is a very small part of trucking. If you look at the average truck on the motorway—take the M1 or whatever—it is probably not going over 500 miles. Five hundred miles is about where you would worry about electric trucks. If you look at the decisions being made by companies like Scania and so on, they are looking to anything shorter distance than that being electric because the technologies are proven and the trends are clear. When you get to the truly long-distance trucking, you have to look at whether it can be done and where you would put the charging infrastructure. Technically, of course, it can be done. You can have rapid chargers. You could do those long distances, but you might want to have a discussion about hydrogen for very long-distance trucking, and you would have to do it with European partners. You cannot have a situation, as with the railways, where the gauge changes when you get across the border. Co-ordination is needed.

Q54 **Chair:** Thank you very much indeed. I would like to follow up on a couple of the points made. Michael Liebreich, you talked about the advantages that places with the possibility to host large solar arrays have, whether that is sub-Saharan Africa or Australia. Does that mean that, if we base our energy system significantly on hydrogen, we are liable to be importing supplies of hydrogen from places that have an intrinsic cost advantage in producing it?

Michael Liebreich: If you import hydrogen via a pipeline, it is pretty cheap. If you import it any other way, it will be very expensive. To the extent that there is a global system of imports and exports, it will overwhelmingly rely on pipelines. You can put it on ships. You can do all sorts of things. You start to add. If you are aiming for $1 per kilo or $1.5 per kilo for the hydrogen, and you start putting it into a ship, whether it is under high pressure, liquefied or turned into something else for transport, you might be adding another $2 to $5 per kilo. In other words, the price shoots up.

The best way I know to help think through this is to use the lens of what job it is you want the resource to do. What is the job you are trying to do? You are trying to heat homes. You are trying to make steel. You are trying to drive a truck. There is something you are doing, and then work out what the cheapest, best and most resilient way is to do that. Will we be importing? It is possible that we could do hydrogen from the North sea, maybe turn it into ammonia for shipping and so on, and store a whole bunch of it in bulk, at large scale—in fact, there is a company looking at storage in an offshore formation, the old Rough gas field, but there are also salt caverns—and we could be using that to decarbonise large parts of the UK economy.

If the Australians can then dump hydrogen or ammonia into the UK cheaper, just as we did with coal, we have to admit that we will not get a competitive advantage in our other industries by using high-cost UK hydrogen or ammonia. Australia will not be able to do that, because there won’t be pipelines. There will be only shipping, and the question will not arise. North Africa might be a bit different.

Q55 **Chair:** Dr Baxter, right at the beginning we had this question of the efficiency of producing hydrogen, and you very appropriately pointed out that it depends on what it is compared with. If you were to make that comparison with the existing fossil fuels, how does it compare in terms of the efficiency of production?

Dr Baxter: With some fossil fuels, it is fairly equivalent. You get a better efficiency from gas turbine electricity production and the use of gas in the gas distribution system. We are trying to remove fossil fuels from our energy system, and that often gets forgotten in the debate, and the debate becomes about what the final solution is.

I agree with Michael on the imports. Pipeline really is the only way. If you start to cool hydrogen down, you lose even more efficiency, you are using more energy to do it, and it boils off in transportation as well, so it is not really a good solution from that point of view. We can certainly internally make decisions on subregional travel, whether that is small aircraft, long-distance buses, or whatever we do here. When we work with our European counterparts, we have to make a decision on what that infrastructure looks like. They are all having the same conversation that we are. We have to make sure that we do not go too soon on one solution if they then decide on something else altogether.

Chair: Thank you very much indeed. I thank both of our witnesses for contributing your expertise to the beginning of what is clearly shaping up to be a fascinating inquiry, and we are very grateful for your guidance today. Thank you.

Examination of witness

Witness: Baroness Brown.

Q56 **Chair:** Finally, I want to turn to our last witness of the morning. I am very pleased to welcome Baroness Brown of Cambridge, also known as Professor Dame Julia King, who until last week was Deputy Chair of the UK Committee on Climate Change and is the UK's low-carbon business ambassador. She has been a great contributor both in public policy terms and research terms to these debates for some time. Thank you very much indeed, Baroness Brown, for joining us.

I saw that you were listening in to some of our previous evidence. From your experience as Deputy Chair of the Committee on Climate Change, would you tell us what your expectation is of the role of hydrogen in attaining net zero?

Baroness Brown: In our central scenario for achieving the Sixth Carbon Budget, and going on to net zero, which was published in December last year from the Committee on Climate Change, we have a requirement for about 225 TWh of hydrogen by 2050. It is probably easiest to put that in the context of how big our electricity demand is today. It is around 300 TWh per year. The hydrogen industry is approaching the size of today's electricity industry—a bit larger than two thirds. It is a significant chunk. By this time, by 2050, we will have an electricity demand that will be double the size it is today, because of the electrification of transport and some of our heating and industrial processes. That is about 600 TWh of electricity and something of the order of 200 TWh to a maximum of 300 TWh of hydrogen.

Q57 **Chair:** You have heard some of the evidence that we have taken this morning. A lot of it was around the uncertainty and how dependable it is to count on hydrogen being an important component. What work has the Committee on Climate Change done looking forward as to how reliable this can be as a source of energy?

Baroness Brown: By 2050, we see the major uses of hydrogen being ammonia in shipping and for decarbonising industrial processes, particularly where you need very high-grade heat, which would be difficult to do with electricity. Those are the two main uses. We see some being used for electricity generation in gas turbines for peak lopping and at times when the wind levels are low. We see relatively small amounts of that use in 2050 being potentially in specialist transport uses, some for building heating, but, again, not the dominant uses. The shipping industry is very much looking at ammonia produced from hydrogen being the net zero shipping fuel. Certainly, there are a number of industries we have looked at where electrification will be difficult and hydrogen will provide a solution.

It is not this myriad of things. It is not hydrogen as a magic solution for everything. It is that there are some very key areas where it looks like being a very important player.

I would say that we are not going to get to 200-odd TWh very quickly. We already use some 27 TWh of grey hydrogen today in things like fertiliser production, ammonia production, and chemical production. We already have a demand of approaching 30 TWh. Our projections, and indeed the Government’s strategy, suggest that by 2030 that might have moved to 40 TWh. This is not an enormously rapid acceleration over the next 10 years while we are establishing which of these applications will be the ones that are successful and a highly efficient use of energy.

Q58 **Chair:** One of the questions we have been grappling with already this morning is the extent to which there should be a technology-neutral approach by Government or whether they should select particular technologies because of their promise or because of other strengths in that—picking winners, as it is sometimes called. Is this something that the committee or you personally have a view on that you have considered?

Baroness Brown: I do not like the phrase “picking winners”. There are a limited number of technology solutions that will be available and mature by 2050 that we can use. It is pretty clear that hydrogen will play a role in those. There are some areas where it is not yet clear, and we need to get on with trials through the 2020s. For heavy transport, will electrification be feasible, or will hydrogen be a better solution, or will we have a mixed economy where we have both solutions operational? We need the trials to find out some of these things. It is clear that there are areas where hydrogen will be critical for us.

Q59 **Chair:** In terms of the timetable for that, to what extent do we need to make those decisions now if we are to get to where we need to be by 2050, or to what extent can we defer some of those decisions until there is more evidence from some of the trials?

Baroness Brown: We really have to be making those decisions through the 2020s. We have the next five to seven years to really get a move on with those trials. In our scenarios, as I say, there is a fairly modest growth in hydrogen use to the 2030s, and it accelerates very rapidly from 2030 onwards. We have the next few years to really start getting on with those trials. We see that with the truck manufacturers, for example, who are now moving to get on with establishing which technologies they think will be effective.

Q60 **Chair:** What is the evidence that we are looking for to be able to make policy decisions? Is it about science? Is it about the scale-up of technology? Is it about the economics of it? What are the most important lessons that we are looking to learn from these trials?

Baroness Brown: It is not simple. It is a mixture of all of those things. We clearly need to bring hydrogen production down the cost reduction curve. At the moment, it is very expensive compared with electricity or methane because we are making it from electricity or methane. We have to really bring down the cost down. We have to explore how effectively and how cost-effectively we can transport the hydrogen. We have to look at issues such as how efficient we can get local generation of hydrogen by electrolysis, for example, at fuel stations on motorways. How does that compare with the enormous amounts of electricity you would need to fast-charge the Tesla lorry with the mega-batteries in? We really need to understand the feasibility and the different economics of these different solutions.

Q61 **Chair:** You mentioned the use of grey hydrogen, as it has been termed. Is it a no-regrets policy for the Government to look to convert the production of grey hydrogen into low-carbon hydrogen, whether that is green or blue?

Baroness Brown: Yes, because these are processes that we need to decarbonise. We have a demand to start with. We also have another very useful thing to do. Because it is a challenging situation in a new industry where you are developing demand and supply at the same time, another useful transitional thing we can do is to be able to put up to 20% of hydrogen into the current gas distribution system. That does not decarbonise heating in our homes, but, as an intermediate step that reduces our CO_2 emissions in the short term, it is a place you could put an awful lot of hydrogen. If the shipping or some of the other demands do not come along at quite the rate that you expected them to, there is something you can usefully do with an excess of hydrogen.

Q62 **Chair:** What about the argument that that fudges the decision as to whether you should be aiming for a domestic network for hydrogen for heat, for example, rather than grasping the nettle and having an electricity-based domestic heating system, whether that is through the grid and green generation or through heat pumps? Is the danger of incremental additions of hydrogen to the existing system that it defers the decision that needs to be taken?

Baroness Brown: There is some danger that we could use it in that way, and it would be very disappointing if we did. On the other hand, we need to recognise that CO_2 emissions accumulate, and that is what increases the global temperatures. The sooner we can cut CO_2 emissions, the better. Doing that now, and reducing emissions now, is a beneficial thing to do from a climate change perspective. I agree with you. If we can do it, the most cost-effective way to heat buildings is through electricity with heat pumps, but we have to recognise that we have an extraordinary historical building stock in the UK. We have some of the worst-insulated buildings and homes, particularly, in the UK. There is an enormous job to do to insulate them before, in many cases, we can heat them effectively with things like heat pumps.

Q63 **Chair:** Thank you very much indeed. Before I turn to my colleague, Carol Monaghan, you have commented in the past that the UK needs to have a hydrogen strategy and that there has been a piecemeal approach taken so far. What is your assessment of the plans that have been published? I am thinking in particular about the 10-point plan. Does this satisfy the need, or do the Government need to go further?

Baroness Brown: I think it is a good start. The 5 GW of low-carbon hydrogen by 2030—which is about 44 TWh of hydrogen by my calculations, but the Energy White Paper calls it 42 TWh—is about the same level as in the Committee on Climate Change's latest core scenarios for getting to net zero. It very sensibly says that we are getting on with the things that Michael Liebreich was talking about, which is developing the right business models. We are told that the business models will be published in 2022.

There is quite a strong focus on hydrogen heating trials. In our Committee on Climate Change core scenario, we end up with something like 11% of homes in the UK being heated with hydrogen, which is a significant number of homes but it is nothing like all of them. We need those trials, but I would like to see a more balanced focus on the trials and a stronger focus on linking things like the low-carbon buses the Department for Transport talks about to the hydrogen strategy as well as to an electrification strategy, so that we make sure we are taking a completely integrated approach right across different Government Departments. We have not seen enough of that, and we need to see more of that.

Chair: Thank you; that is very clear.

Q64 **Carol Monaghan:** Baroness Brown, the Government have announced targets for hydrogen production. I think it is 1 GW by 2025 and 5 GW by 2030. These seem quite modest to me. Are you confident that they are ambitious enough?

Baroness Brown: Five gigawatts is the figure that I was focusing on. If you assume that is 5 GW operating 24/7, then that is 44 TWh. The Energy White Paper says 42 TWh. That is about the level that we have in our core scenarios from the Committee on Climate Change for reaching net zero and also the Sixth Carbon Budget. Our scenarios see a very steep rise between 2030 and 2035, and hydrogen production rising very steeply beyond that. As a kind of "Where can we get to by 2030?", we think that is not an unreasonable number. I think in terms of—

Q65 **Carol Monaghan:** Just before you go on, Baroness Brown, as a comparison, what are we dealing with now in terms of our energy needs in terawatt-hours? What percentage of our energy needs would this give us?

Baroness Brown: I do not have that figure in my head. Our current electricity demand is about 300 TWh. The demand for gas is considerably more than that, but it is very cyclical. The demand for transport fuels is also larger than that.

Carol Monaghan: Thank you. Please go on.

Baroness Brown: I am sorry, I have forgotten what you asked.

Q66 **Carol Monaghan:** I was asking if those targets were ambitious enough. Apologies for interrupting.

Baroness Brown: Five gigawatts would be a huge nuclear power station. It is a big hydrogen nuclear power station, if you like to think of it like that. If we want to get hydrogen down the cost reduction curve, if you think of how many gigawatts capacity of electrolysers we need, we should not see 5 GW as meaning we only need 5 GW of electrolysers. Particularly if we are using the otherwise curtailed renewable energy that we might get from solar in the middle of a summer day or from offshore wind at a time when we do not need it, we could be using that with electrolysers to produce green hydrogen. We could potentially need a lot more than 5 GW of electrolysers because they will not be running 100% of the time. In terms of helping our industries develop and helping us get round the cost reduction curve, we are not saying that we only imagine there will be 5 GW of electrolysers installed, for example. The numbers could be much larger than that.

Q67 **Carol Monaghan:** You mentioned green hydrogen. Is the Government's balance of green to blue hydrogen appropriate?

Baroness Brown: The Government have not given a balance of green to blue hydrogen. I fully support the Government in looking at developing both as a starting point, and we certainly have that in our Committee on

Climate Change projections. We get to 2050 with still some blue hydrogen. By 2050, we are at something like 40% green hydrogen, 35% blue hydrogen, and some of the rest coming from bioenergy to hydrogen processes. We think there will be more electrolytic hydrogen by 2050. On the way to 2050, in a way, we need to see how quickly we get carbon capture and storage working, and how quickly we get electrolysis with offshore wind working, for example. They may grow at different speeds on the way to 2050, and that is quite hard to predict.

Q68 **Carol Monaghan:** When hydrogen started being raised as a potential fuel and a potential alternative to our current energy sources, there was a narrative that hydrogen was, of course, very green. There was not a discussion of green versus blue hydrogen. There is probably still some lack of understanding among many—possibly politicians, but definitely members of the public—who assume that hydrogen is far greener than it is. Is there a need for the Government, when we are talking about 2050, to have specific targets for blue and green within that? You have said yourself that there is a danger that the balance will shift as we go through that. Is there a danger that, if we do not have targets in place, we will not see the shift happening as quickly as we need it to?

Baroness Brown: We will see the shift happening. At the moment, we have an electricity grid that is about 30% variable renewables, and sometimes they need to be curtailed, because they are not generating when we do not need the electricity. By the time we get to 2050, our core scenario for CCC says we could have a grid that is 80% variable renewables. How much hydrogen we would want to make from electrolysis will grow as the renewables on the grid grow. The target of 40 GW of offshore wind by 2030 is a very critical one. Offshore wind then grows very fast, in our scenarios, to something around 100 GW by 2050.

As you do that, you have more and more times when the generation on the grid will be curtailed because there is a lot more generation than we are using. That is when you start to be able to generate really cheap electrolytic hydrogen because, essentially, the electricity may even have a negative price at some of those points. It is quite logical for the electrolytic hydrogen to be growing as the renewables on the grid grow. If you were going to be setting targets, that is probably where you might be putting them. That growth will not come very rapidly in the next five or six years. You then have the opportunity that, as we develop these carbon capture and storage clusters, it may be possible to develop the blue hydrogen industry, at times more quickly, while we are waiting for the balance of the grid to change.

Q69 **Carol Monaghan:** Why do you say it will not grow for the next five years? Is it because of the amount of renewables currently in the grid?

Baroness Brown: Because it is so closely connected to the rate at which renewables on the grid will be increasing.

Q70 **Carol Monaghan:** There is really a requirement then to up our investment in renewables in order to produce our green hydrogen.

Baroness Brown: There will be. We already have an ambitious target of 40 GW of offshore wind by 2030, which will be a very important start to this trajectory. At the moment, we have about 10 GW of offshore wind operational. That is quite a steep increase already. You asked how "green" the hydrogen is. It will be critical that the carbon capture and storage is initially giving us blue hydrogen where at least 95% of the CO_2 has been captured. As we get towards 2050, we would want that to be moving towards 99%. If you have blue hydrogen with 99% CO_2 capture, then that is a pretty good, low-carbon fuel.

Q71 **Carol Monaghan:** Will the strict production targets that we have already talked about make it difficult to balance the growth in supply and demand?

Baroness Brown: I am sorry, I did not quite understand the question.

Carol Monaghan: Would these targets make it difficult to balance the growth in supply and demand? Will we limit the demand for hydrogen if we only have 5 GW as our target, for example? If we have a more ambitious target, we might increase the demand for it.

Baroness Brown: As I say, it is at about the level—in terms of our analysis of how quickly some of these industries can grow and providing the CCC advice—that we see industries being able to grow by 2030. We see it as at about the right level. We do not see it as a rigid target. If industries develop faster, there is a possibility this could be larger. We should not see it as a restrictive "There will be no more than 5 GW." It is a pretty good stake in the ground for saying that that is a realistic and sensible level.

Q72 **Chair:** Baroness Brown, you have been drawing on your experiences on the Committee for Climate Change in thinking about the 2050 agenda, but you are also one of our most prominent and successful engineers. You were vice-chancellor of Aston University for 10 years. Thinking about the industrial strategy aspects of it, what is your assessment of the opportunities for the UK? I do not want to be sentimental about it. Is this an area in which we have particular comparative advantage, or is it not the case? Michael Liebreich, in the previous panel, talked about some of the advantages that places with a lot of sunshine have in being able to electrolyse water to produce hydrogen. What are the prospects for the UK? Are we advantaged or neutral, or disadvantaged relative to other countries?

Baroness Brown: Now you get me on to a topic for which I am a great enthusiast. This is an area where we are advantaged. We have fantastic offshore wind resource around the UK, with some estimates of approaching 1,000 GW but certainly 600 GW in UK waters. We have an amazing wind resource. It is cheap already and getting cheaper. It may not compete with solar in Australia or some other places, but Michael highlighted, I thought very well, the cost of transporting hydrogen over long distance, particularly via shipping, and we have looked at that in the CCC work. While we think there might be some small imports into the UK, they would be relatively local if they were to happen for that reason. We have a great offshore wind resource that can be used for electrolysis.

Because of our geology, we also have a huge resource for storing captured CO_2. We are also a good place for producing blue hydrogen, and, if we can get right up to those 99% capture rates, it is probably a good way of making hydrogen relatively cheaply.

We also have a fantastic industrial base for doing this. Unlike offshore wind, where all the original equipment is designed by people in other countries and where all the developers are from overseas, in the UK we have a strong oil and gas industry that we want to see converting to low-carbon hydrogen; we have Johnson Matthey, a FTSE 100 company, that makes all of the key components for batteries, but also makes fuel cells, and works with all the key metals that will be critical in these systems.

We have companies like Wrightbus and Alexander Dennis. We have ITM Power, a leader in PEM electrolysers, which are the right sort of electrolysers for using with an intermittent power supply. We have Ceres Power and Intelligent Energy, which make fuel cells. We have a large number of emerging companies like H2GO, Riversimple, Microcab and Ryse Hydrogen. We have a fantastic academic base in areas like electrochemistry in UK universities and also in the systems modelling that you need to understand how a hydrogen system might work.

Actually, we are in a very strong position in the UK. If we get the timing and the Government support right for this, it gives us an opportunity to do something that we have not been able to do, for example, with offshore wind, which is to ensure that we design and manufacture some of the really key components and systems for future hydrogen production.

Chair: Fantastic. That is a very good note on which to draw this session to a conclusion. We are slightly over time, but we are grateful for your indulgence. This is the first public evidence session we have taken on this inquiry. To have the technological aspects, the climate aspects and also the industrial policy aspects brought to our attention today is a great start. I am very grateful, as ever, for your evidence today. I hope you will allow us to continue to pick your brains during the course of the inquiry before we make our report. Thank you very much indeed and thank you to all Members. That concludes this meeting of the Committee.