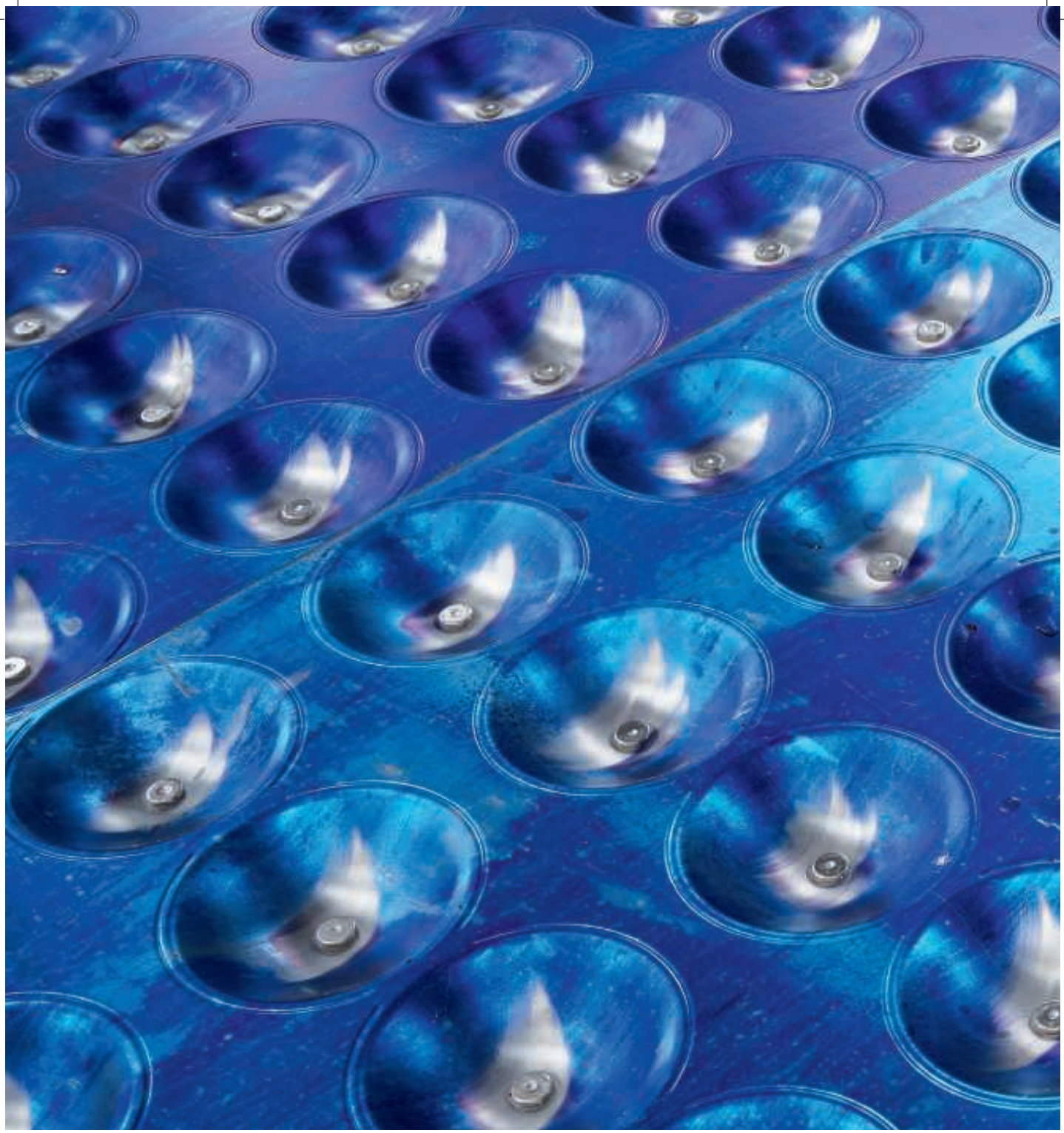
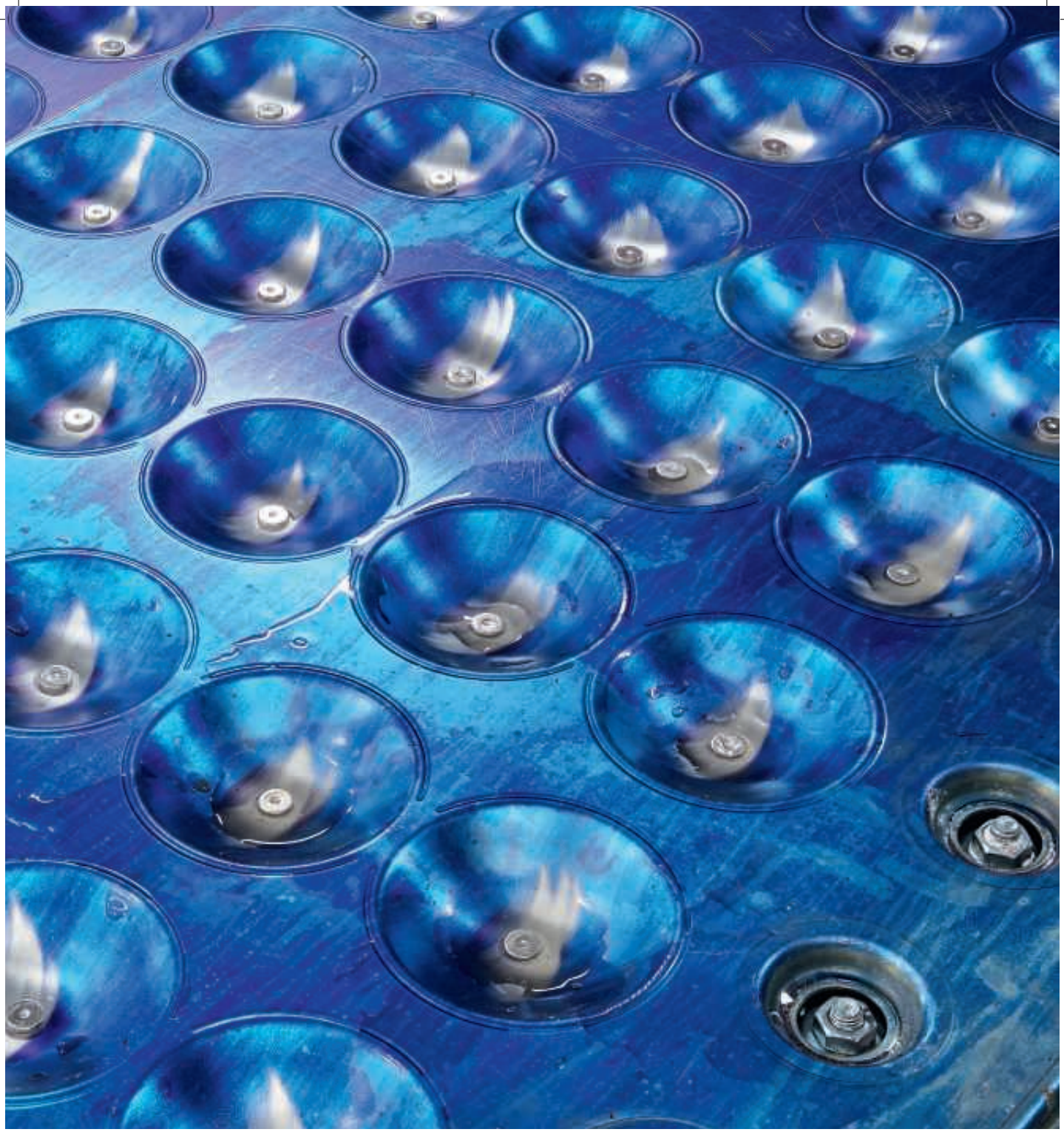


CELL DIVISION



Hydrogen fuel cells were hailed as the future of road transport, even as they powered the space shuttle into orbit back in the 1980s. Yet for decades they've been overshadowed by electric vehicles using lithium-ion batteries. Paul Horrell assesses where the technology is at now and whether a comeback is on the way *Photographs by Greg White*

So to start, a precautionary tale on not counting your fuel cells until they're hatched...

Looking back, the optimism is borderline reckless. Especially from a company such as Daimler-Benz. In the early 1990s the brand was working up the idea of a small Mercedes, and product planners actually reckoned it was worth packaging the whole thing around a powertrain that didn't yet exist. The A-Class was conceived with a void under the passenger floor, ready for a set of hydrogen tanks to feed a fuel cell (FC).

Inevitably the W168 and succeeding W169 ended up as combustion-only cars. Much of the underfloor space went to waste – although it did allow for the model's wonderful shortness, serving as a handy receptacle for a rearward-flying engine during a crash. Unfortunately, the tall proportions didn't only cause the initial elk-test debacle, they were insufficiently alluring to buyers. So for the third-generation A-Class, Mercedes capitulated, dropped the novel construction and turned it into a Volkswagen Golf-a-like.

During the last decade of the previous century and the first one of this, Mercedes was one of the global leaders in alternative-drive research. Actually, the Vision A concept car that previewed the A-Class was battery electric, powered by a novel high-temperature salt battery held at an internal temperature of 245 degrees C. Later on, there were a few electric versions of the related B-Class, using Tesla's technology. But back in the 1990s these cumbersome batteries must have made pure-electric cars look pretty unfeasible, whereas fuel-cell electrics were where it was definitely at. So said engineers from Stuttgart to Detroit to Toyoda City. I even drove an A-Class prototype with the fuel cells. Oh hang on, that isn't quite so. I went on the press event, but of the dozen of us hacks there, I recall only one had a go before the car went on the fritz.

Of course, it's not the carmakers' fault that we are still waiting for fuel cells to hit the streets

In 2012 I interviewed Dieter Zetsche, former chief engineer and by then CEO of Mercedes. Why had fuel cells not happened? Infrastructure, he said. If Germany had installed hydrogen stations, the chicken-egg quandary would have been resolved. The public would have found it worth buying a fuel-cell vehicle (FCV) because they'd have been able to refuel it. So the cars would have moved from lab-scale to factory-scale, and the prices would have fallen. "Cost-wise our target is to be similar to a diesel hybrid, and we're not there. But five years is realistic." That'd be 2017 then. And the engineers were shrinking the powertrain's size as well as cost, so it could fit into normal floorpans. To have installed enough hydrogen filling stations for Germany, he reckoned, would have cost as much as the bank bail-out of a couple of years earlier – which had drained any government's ability to subsidise new-energy projects.

But of course that wasn't the only reason you don't have a hydrogen filling station round the corner, and aren't pondering the option of fuel-cell drive for your next car.

This is the bit where Elon Musk enters the tale

Just one thing did for the prospects of the FCV. The Tesla Model S. While talking about hydrogen infrastructure in 2012, Zetsche said, "Battery vehicles are basically just for small cars and city use, and FCVs are a solution to that limitation." Zetsche wasn't being German-snotty about the California start-up, by the way – he presided over a cross-shareholding and later acknowledged Tesla's huge lead in battery-electric vehicles (BEVs).

Saying that battery power was just for city use and fuel cells were for 'proper' cars was absolutely the car-industry wisdom at the time. Nobody except Tesla, planning 250-mile battery packs and the ultra-fast Supercharger network, could even begin to imagine an electric car for a road trip.

The 'jam tomorrow' conundrum

Ballard Power Systems was formed as a lithium-battery research company, but – oh the irony – it switched horses to proton-exchange-membrane fuel cells. By the turn of the century it was seen as the go-to company for that technology by German and American carmakers. In early 2000, Ballard Power Systems' share price hit £144.98. Two years later it was in the $30 range. From 2009 to last year, it seldom scraped above $3.

Can you remember the first time you read that mass-market adoption of fuel-cell cars was 15 years into the future? I can't. But I fancy it was around the late 1990s, the same time I started driving one or two fuel-cell prototypes a year. Proof-of-concept machines have been turning up at motor shows ever since, most notably from Mercedes, GM, Toyota, Honda and, more recently, Hyundai. Some of them went into low-volume production. But probably no more than a few thousand vehicles, total, have seen the light. Here we are, after a quarter-century staring at a rolling horizon; still being told that mass adoption is 15 years into the future.

Was there ever a technology in which so much was invested, for so little return?

Yet still the dream of FCVs persists, particularly in trucks

Despite all this, there's still something about fuel-cell cars that sticks like Velcro to the imagination. Maybe it's the scientist-fantasy notion of the 'car that emits only water'. Maybe the comforting familiarity of a five-minute fuel stop where you pump fluid into your tank. (And best not dwell on the fact that the fluid in question is a gas at 700 atmospheres pressure.)

Fuel-cell stories keep cropping up in the engineering news. Carmakers keep quietly investing. Hyundai's Nexo is a proper consumer-grade crossover hampered only by the scarcity of places to fill it up. Toyota, having proven that the Mirai works, is leading with this tech in a BMW co-op that in 'the second half of this decade', BMW says, could put fuel cells into its bigger SUVs. GM and Honda, two of the early starters in all this, have a fuel-cell research and manufacturing joint venture. Audi is working with Ballard, whose share price has lately breached $10. The Chinese Government has put subsidies in the billions of dollars into fuel cells. Weichai has bought a near-20 per cent stake in Ballard, and the two have established a JV to make fuel cells for trucks for China.

Heavy trucking looks like a really good place to start with fuel cells, notwithstanding the endlessly delayed electric Tesla Semi. Weight is critical, and hydrogen – even in its heavy tanks – is more weight efficient than battery packs. Trucks often work pre-defined routes between depots that can be outfitted with the hydrogen pumps – and so, of course, do the 400 or so fuel-cell buses across

HEAVY TRUCKING LOOKS LIKE A REALLY GOOD PLACE TO START WITH FUEL CELLS, WEIGHT IS CRITICAL, AND HYDROGEN – EVEN IN ITS HEAVY TANKS – IS MORE WEIGHT EFFICIENT THAN BATTERY PACKS. TRUCKS OFTEN WORK PRE-DEFINED ROUTES BETWEEN DEPOTS THAT CAN BE OUTFITTED WITH THE HYDROGEN PUMPS. AND IN THE RIGHT PILOT AREAS, THE HYDROGEN TO THOSE PUMPS CAN BE RENEWABLE

Previous page: The titanium shell of an anode, which is one part of a module. A module consists of an anode, a membrane and a cathode. Multiple modules make up an electrolyser that produces chlorine gas at the anodes and hydrogen gas at the corresponding cathodes

European cities. And in the right pilot areas, the hydrogen to those pumps can be renewable. Hyundai has developed a 34-tonne FC truck, with a 300-mile range on a seven-minute refill. It's deploying a fleet of them in Switzerland, where hydro-electric dams supply the green energy for hydrogen production. Under the Swiss tax regime, it makes the trucks as cheap to operate as diesel vehicles, and they don't emit toxins or CO_2. Meanwhile, in April 2020, Volvo Trucks and Daimler announced a $1.2 billion joint venture to develop and build FC systems for trucks.

But how does anyone make money from hydrogen fuel and FCVs?

Hyundai sees trucks as a critical pathway towards priming the relevant infrastructure. Breaking even on a hydrogen filling station needs 700 cars'-worth of their annual mileage. But it's just 15 trucks'-worth, because they use more hydrogen and drive further. Plus, of course, building trucks and buses chases down the scale economies for the FC stacks and tanks. Hyundai-Kia's head of fuel cells, Sae-Hoon Kim, says, "At around 200,000 units a year, you get the scale to buy the materials you need at a price that puts costs on par with today's battery-electric vehicles."

By 2030 his company is planning to have installed a half-million annual production capacity for fuel-cell cars, trucks and buses. South Korea's trade and industry ministry has just released a plan for 300-plus hydrogen stations by 2022 and 1200 by 2040. And as we all know, what the Koreans plan, the Koreans tend to do.

While the UK currently has fewer than 10 hydrogen stations the public can use, Germany has quietly got itself 85. This was the vision of Wolfgang Reitzle, the former BMW chief engineer who famously went via Ford's Premier Automotive Group to Linde, the industrial gas group. (It's amusing to think that Reitzle and Zetsche, the chief engineers responsible for the 1990s face-off between BMW's and Mercedes' car ranges, nearly became the twin actors to get fuel-cell models off the ground. Mercedes's vehicles being the chicken, Linde's hydrogen the egg. Or vice versa.)

Now in 2020, something's been happening – or rather, not happening – with battery-electric vehicles. Batteries keep improving, but real breakthroughs turn out to be awfully hard to come by. Solid-state cells couldn't deliver Dyson his hoped-for profit. Apple has shied away. Tesla keeps building battery plants, but not new battery types.

While they still have plenty of hurdles to jump, FCVs could eclipse BEVs in the long term

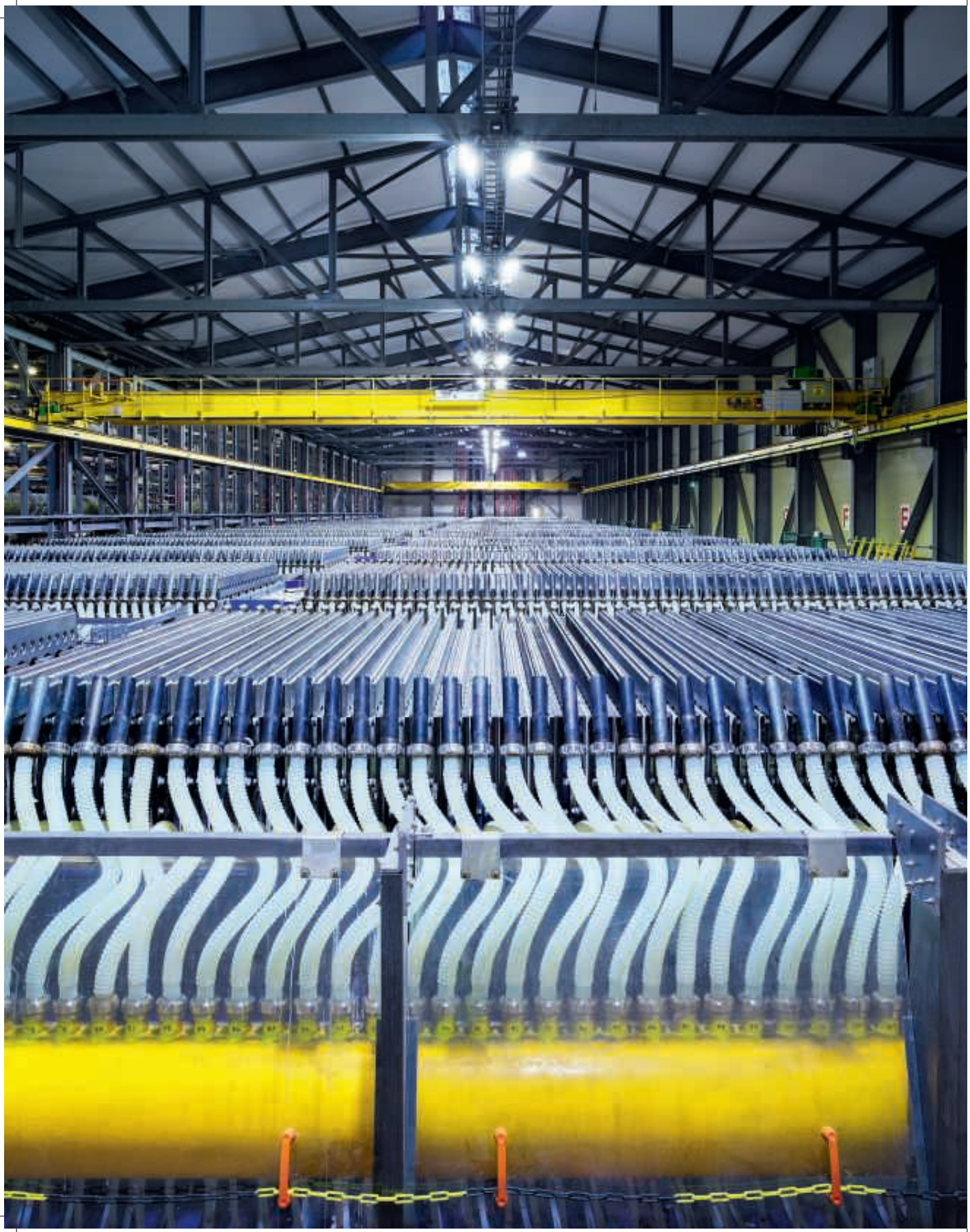
Whatever its advantages, hydrogen is still an easy fuel to take shots at. The most common objection is simple. Efficiency. Take a kilowatt hour of electricity, ideally generated renewably. Put it into a battery car and you'll get nearly three miles. Take that same kWh, use it to electrolyse and compress hydrogen, then put that into the FC car, and it'll take you just over a mile.

And, of course, electricity is in your wall. Plug in your car overnight and you'll have 200-plus miles'-worth of energy come the morning. It's enough for the vast majority of us on the vast majority of days. Hydrogen doesn't come out of a domestic socket. It needs stations, like petrol. So hydrogen is going to have to parry back with some pretty compelling advantages if it's to overcome the drawbacks of efficiency and availability.

In its favour, and somewhat counter intuitively, if the electricity isn't renewable, the CO_2 emissions from a fuel-cell car are the same as a battery-electric car's. At the moment a lot of hydrogen is produced from natural gas, which is reformed at the station. This produces CO_2. But the US's Union of Concerned Scientists' calculations show that roughly the same amount of CO_2 per mile is emitted from driving an FCV on this hydrogen as from driving an EV on electricity generated in natural-gas power stations. Get the hydrogen from electrolysis fed with electricity generated from biomass combustion and carbon capture – as with Yorkshire's giant Drax power station – and it becomes carbon negative.

Then there's the manufacturing. An argument commonly levelled against battery EVs is that making their batteries takes a colossal load of resource – energy, minerals – versus building a petrol car. By some calculations (but by no means all), this manufacturing debt is never repaid over these vehicles' lifetimes, especially not the ones with high-capacity batteries for long range, which are the very kind of car FCVs would best replace. But a fuel-cell car has only a small hybrid battery. The costs of rare-earth metals needed by the stacks are falling, along with manufacturing cost. [CONTINUED ON PAGE 91]

A boiler plant which can switch between operating on natural gas or hydrogen, depending on the availability of hydrogen from the cellroom



NO ONE'S IMAGINING BATTERY CARS ARE GOING AWAY, BUT NO ONE THINKS THEY'LL BE THE ENTIRE ANSWER. BMW'S CHIEF ENGINEER KLAUS FRÖHLICH WAVES AT HIS PROTOTYPE FUEL-CELL SUV AND SAYS IT'S A LONG GAME. "HYDROGEN FUEL-CELL TECHNOLOGY COULD FEASIBLY BECOME THE FOURTH PILLAR IN THE LONG TERM," THE OTHERS BEING PISTON ENGINES, PLUG-IN HYBRIDS AND BATTERY-ELECTRICS

Left: The cellroom containing multiple electrolysers. In the photo you can see the individual modules and exit hoses that make up each electrolyser, where chlorine gas is produced at the anodes and hydrogen gas evolves from the cathodes (*All photos taken at the INOVYN Runcorn Site, Cheshire*)

And don't forget, hydrogen can be moved using existing pipelines

Finally, but maybe critically, hydrogen has a conceptual advantage. Electricity is energy. Hydrogen is an energy carrier and storage medium. As the world moves towards renewables, the supply of energy will get more prone to uncontrollable fluctuation. Stored hydrogen would be a handy buffer.

Hydrogen is also transportable. "It's generally easier to move molecules than electrons," says Mike Dolman, of Cambridge-based low-carbon energy consultant Element Energy. "The model is to co-locate electrolysis with green electricity and exploit renewable resources you can't otherwise use." We have a national grid, yes, but we have no means to get renewable electricity via cable from distant sources to the countries where the cars are. That applies whether it's generated by wind in Scotland or solar in a post-oil Middle East. Hydrogen pipelines are feasible. In fact, you can re-purpose old natural-gas pipelines to do the job, installing power-to-hydrogen equipment beside wind turbines where the North Sea rigs now stand, and use the existing pipelines. "You can move the wind turbines further offshore," adds Dolman.

Stephen B Harrison worked for Linde under Reitzle, and now consults as sbh4 GmbH. "Distribution of liquid hydrogen is possible. It can be shipped like liquefied natural gas can. Or it can be transported as ammonia. The technology is no big deal." He also says production is getting cheaper. "Ten years from now the economics of production could be very different. Electrolysis via PEM [polymer electrolyte membrane – essentially the reverse of what happens in the car's stack] is not mature yet on an industrial scale." He points out that the new solid-oxide electrolysers produce high-grade heat as a by-product, which improves the finances. And the PEM kit can work both ways, power-to-hydrogen or hydrogen-to-power, so it does the buffering job.

In Cheshire, a natural underground network of salt caverns has been used to store natural gas for years. Now a pilot is looking at using them to store hydrogen. Remember, it's not like hydrogen is some unfamiliar exotic stuff. INEOS, for instance, makes 250,000 tonnes a year of it, as a by-product of electrolysis for industrial chlorine, and from the cracking of oil into compounds for plastics manufacture. That's enough to propel 2.5 million fuel-cell cars 10,000 miles each.

But why would any commercial entity invest in hydrogen? Harrison raises this point just as the oil price is going effectively negative. "Governments could stabilise investment in hydrogen by putting a floor on the carbon-emissions trading price," he says. That would stop the fluctuations (troughs rather than peaks) in oil-based energy prices that frighten off investors. "Technical issues of production and distribution are not a problem. It's all about energy policy, and that's locked into environmental policy."

Ultimately, what we want is the best of both worlds

No one's imagining battery cars are going away. But no one thinks they'll be the entire answer either, at least not for decades. BMW's chief engineer Klaus Fröhlich waves at his prototype fuel-cell SUV and says it's a long game. "Hydrogen fuel-cell technology could feasibly become the fourth pillar in our powertrain portfolio in the long term," the others being piston engines, plug-in hybrids and battery-electrics. He says no one has a single answer that will cover all car buyers in all regions.

Can fuel-cell power fill a gap, or more likely provide a permanent piece of the puzzle? It's obviously going to take some big decisions – commercial ones and policy ones – before that era arrives. Fröhlich says BMW won't sell such a car until there's enough affordable green hydrogen for the drivers to buy. But there will be a small number of pilot cars based on the X5 from 2022 using technology developed with Toyota.

Over at Toyota, ambitions are different. The company is not just putting cars into production, it's breaking ground on a whole new town called Woven City, powered entirely by hydrogen and solar. Running along similar lines to the 'smart city' model, the place and its population will form a fully immersive 24/7 lab for sustainability, robotics, AI and new urban mobility. It's designed by progressive Danish architect Bjarke Ingels Group, and Toyota is looking for other partners to join the experiment.

So despite being marginalised this past decade, FCVs are making a comeback because the technology remains sound, and they look increasingly capable of filling the gaps left by BEVs. And most importantly, if we're serious about tackling the climate emergency, hydrogen fuel cells provide another, perhaps crucial, means to do it.