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The role of compound semiconductors within the green hydrogen ecosystem

Catapult Compound Semiconductor Applications

UKRI Innovate UK

Hydrogen Innovation Initiative

HII partners:

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Executive summary

In June 2019, the UK became the first major economy in the world to pass laws to end its contribution to global warming by 2050. The government has set out policies to achieve Net Zero as well as investing in wind, solar, and hydropower to increase the generation of electricity from renewable sources. They are also encouraging the development of green hydrogen and carbon capture and storage (CCS) technologies to reduce emissions in hard-to-decarbonise sectors such as heavy industry and aviation.

The Hydrogen Innovation Initiative (HII) is a cross-Catapult project aimed at creating an interconnected ecosystem that leverages the strengths, resources, and regional presence of organisations to advance the development of a green hydrogen economy in the UK.

HII aims to foster innovation across the entire value chain, from fuel generation and distribution to consumption. One such innovation is the use of compound semiconductor technology in the area of clean energy where implementation can reduce conversion losses by up to 90%.

The Compound Semiconductor Applications (CSA) Catapult is a not-for-profit organisation, part-funded by Innovate UK, that is committed to developing novel solutions to utilise these compound semiconductor technologies across a number of sectors, ranging from future telecoms, intelligent sensing and, crucially, the road to Net Zero.

Working as part of the HII Seed programme, CSA Catapult set out to investigate the potential application of compound semiconductors within the green hydrogen ecosystem and where they might help facilitate the development of a viable supply chain to meet the UK's Net Zero targets.

The green hydrogen ecosystem can be defined as a comprehensive system that encompasses infrastructure, and technologies, with stakeholders involved in producing, transporting, distributing, and utilising hydrogen derived from renewable energy sources. This can include renewable energy providers, manufacturers of electrolysers, hydrogen refuelling stations, transportation systems for hydrogen, and end-users from different sectors, such as energy, transport, industry, and residential applications.

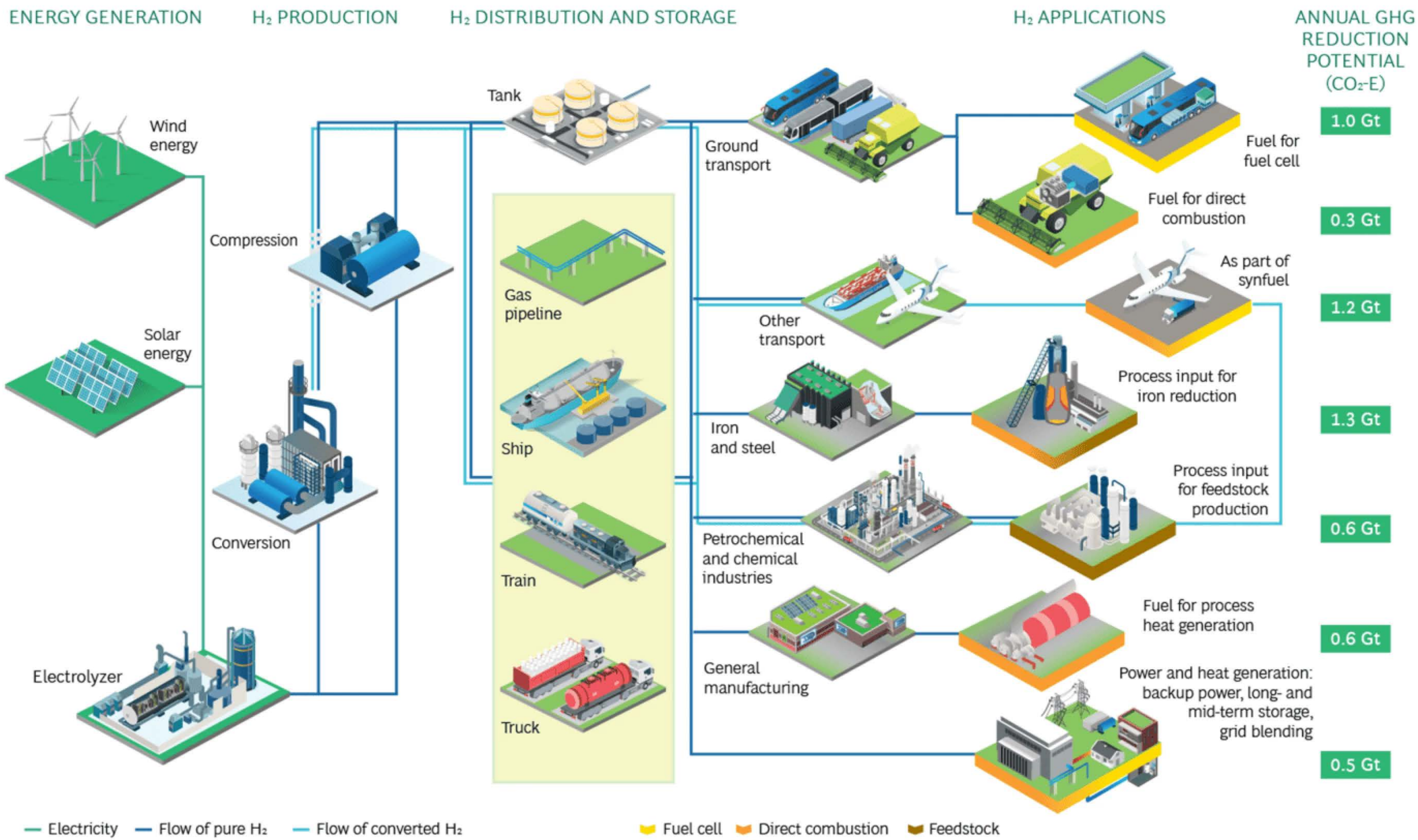
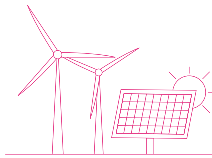
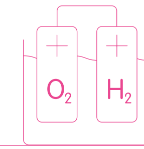


Illustration of green hydrogen ecosystem
(Source: Boston Consulting Group)

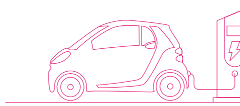
In this white paper we have identified the following areas where the adoption of compound semiconductors could contribute towards a more efficient ecosystem:



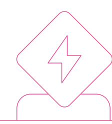
1 **Renewable energy generation:** Both wind and solar technologies can benefit from silicon carbide (SiC), which has superior power conversion efficiency, reducing energy conversion losses by up to 90%. For wind energy, the integration of SiC technology can enhance operational efficiency and reliability. In solar, SiC's heat dissipation properties help extend the lifecycle of solar photovoltaic (PV) systems.



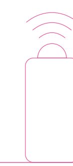
2 **Power electronics for electrolysis:** Electrolysers are crucial to the production of green hydrogen. They use electricity to split water into hydrogen and oxygen. Power electronics convert and regulate the electrical power required. Future compound semiconductors could replace existing silicon devices to improve efficiency and boost electrolyser performance.



3 **Applications in transportation:** One promising application is the use of fuel cell electric vehicles (FCEVs) which utilise a hydrogen fuel cell to generate electricity for powering the vehicle's electric motor. FCEVs offer quick refuelling times, longer driving ranges, and zero emissions. Compound semiconductors have the potential to play a critical role in enhancing efficiency, performance, and reliability.



4 **Enhanced microgrids:** Microgrids are a small-scale power resource that can operate independently or in conjunction with the main grid, enhancing reliability and making use of renewable resources. Notably, hydrogen fuel cell microgrids are ideal for power-hungry applications such as data centres. The addition of compound semiconductors can further enhance the efficiency and performance of these systems.



5 **Advanced sensors for hydrogen detection:** Single-photon avalanche diodes (SPADs), particularly those made of indium gallium arsenide (InGaAs), show promise for gas sensing, including hydrogen leak detection. InGaAs SPADs offer high sensitivity to near-infrared light and the ability to detect single photons, making them suitable for accurately detecting and quantifying gas emissions.

In summary, compound semiconductors offer significant benefits for green hydrogen applications, particularly in FCEVs across the transport spectrum ranging from HGVs to trains and aircraft. Other applications outlined in this white paper may take more time to become commercially viable due to factors ranging from technology readiness levels (TRL) to regulatory challenges and infrastructure limitations.

Another factor that impacts the broader adoption of compound semiconductors is their higher production costs along with associated materials compared to silicon.

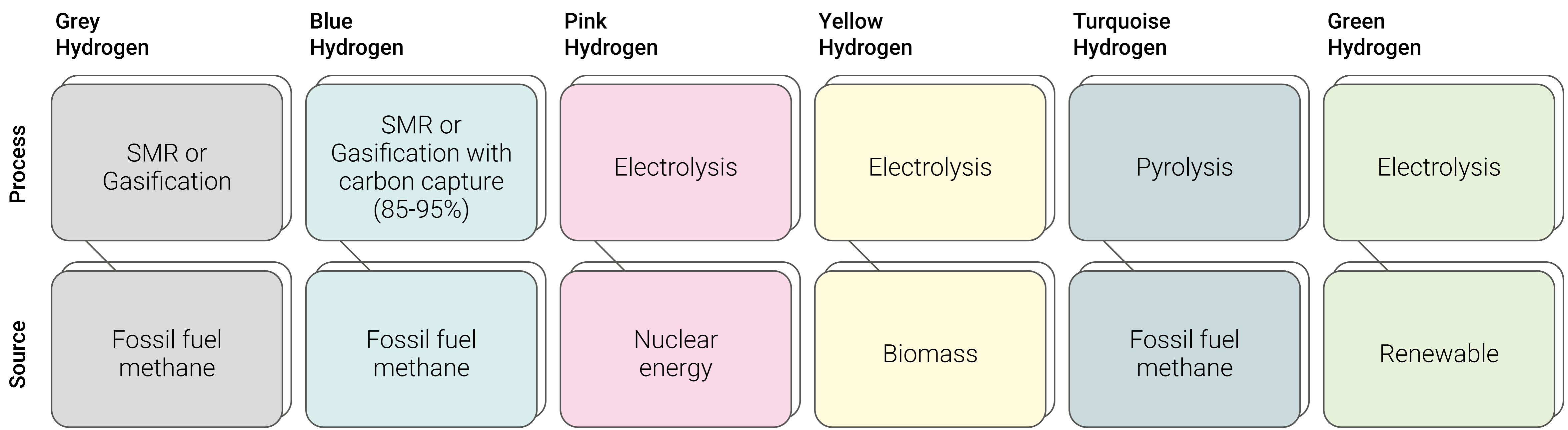
Moreover, there is a bigger challenge related to hydrogen supply, with limited availability and infrastructure for production, distribution, and refuelling across the UK at present.

But by overcoming these obstacles, compound semiconductors have the potential to play a crucial role in enhancing the efficiency and reliability of the green hydrogen ecosystem throughout the production, storage, and transportation processes.

The path to green hydrogen through innovation and investment

Hydrogen is the lightest and most abundant chemical element on the planet. But the process to turn it into liquid fuel is both difficult and expensive to manufacture.

There are six types of hydrogen used in industry, all with different colours across the spectrum to distinguish between their production methodologies.



The most commonly used variant is grey hydrogen which accounts for 90% of all hydrogen produced. It is derived from natural gas or fossil fuels using a process called steam methane reforming (SMR). The by-product of this method is carbon dioxide which is released into the atmosphere, contributing to a country's greenhouse gas emissions.

Meanwhile, blue hydrogen has been gaining a lot of traction as a more environmentally friendly production process. While it still requires the use of fossil fuels to create the liquified gas, the SMR process employs carbon capture and storage (CCS) technology to capture and store the carbon dioxide, reducing emissions by up to 90% compared to grey hydrogen.

Green hydrogen is produced using electricity generated from renewable energy such as solar, wind, or hydropower. Using a process called electrolysis, the water molecules are split into hydrogen and oxygen using an electrical current. The electricity used in the process must be from renewable sources for the end product to be classified as green.

The road to Net Zero will require a significant increase in the use of hydrogen. In 2021, global hydrogen demand rose by 5%, surpassing the previous peak in 2019. The majority of this demand was met by hydrogen produced from fossil fuels, negating its environmental benefits.

By 2030, over half of the world's hydrogen must come from low emission sources if we are to achieve Net Zero. This means producing hydrogen from electrolysis and fossil-fuels combined with CCS facilities.

To achieve Net Zero, over half of the 95 Mt global hydrogen produced by 2030, must be low emission. This will necessitate a significant increase in electrolysis-based production and fossil fuel-based hydrogen production using CCS facilities.

Therefore the ramp-up of the production of green hydrogen is considered a crucial factor in achieving Net Zero by 2050. However, green hydrogen production is expensive, due to the high costs of electrolysers and the need for abundant renewable energy to power the process. As a result, it currently accounts for only a small percentage of the total hydrogen production worldwide.

However, this is set to change, as the UK Government has set out a roadmap to build a world-leading green hydrogen economy. This includes investing in renewable energy sources, such as offshore wind to provide the electricity required for electrolysis, as well as the development of hydrogen production, storage, and a distribution infrastructure.

Through their ten-point plan for a green industrial revolution, the following milestones for low-carbon hydrogen production were set:

- **2025:** production capacity of 5 GW. Enough to power around three million homes.
- **2030:** production capacity of 20 to 35 GW. Enough to power industry, transport, and homes.
- **2035:** production capacity up to 90 GW. Enough energy to meet the majority of the country.

As part of the government's strategy, there are plans to invest up to £4 billion in the development of a green hydrogen industry. This will cover the construction of low-carbon hydrogen production facilities and refuelling stations for transport, as well as the conversion of gas grids to transport hydrogen. Additionally, the government has pledged to support R&D of hydrogen technologies in sectors that are challenging to decarbonise, such as shipping and aviation.

Neighbouring countries have also taken steps towards developing a hydrogen economy. For example, the European Union (EU) announced a hydrogen strategy in July 2020 as part of its Green Deal plan to achieve carbon neutrality by 2050.

The EU's strategy includes investments in R&D, scaling up hydrogen production, and creating a regulatory framework to support the deployment of hydrogen technologies.

Similarly, the United States announced a $2 trillion infrastructure plan in March 2021 that included significant investments in clean energy, infrastructure and the development of a clean hydrogen industry. The plan also provided funding for R&D, infrastructure, and incentives for private investment in the clean energy sector.

China also unveiled the 2021-2035 plan for hydrogen energy development. The Green Hydrogen Policy Dashboard, launched at COP26, shows that governments around the world are starting to set ambitious targets, implement policy, and supply funding for green hydrogen.

While Europe is at the forefront, countries like Mauritania, Morocco, Namibia, and Chile, which possess exceptionally high-quality resources for generating renewable power, are showing a growing interest in green hydrogen.

However, there are still many challenges lying ahead of the green hydrogen ecosystem, which will be elaborated on in the next chapter.

Industrial challenges for a green hydrogen ecosystem

The major obstacle for the wider adoption of green hydrogen is cost. Currently, hydrogen production is more expensive than other energy sources such as natural gas or coal, due to the costs associated with its production, storage, and transportation. To make hydrogen a more viable energy source, it is imperative to reduce the costs of production and delivery.

The production of green hydrogen demands significant energy, predominantly in the form of electricity, to perform electrolysis. The expense of renewable electricity plays a crucial role in determining the overall cost of green hydrogen production. Additionally, the electrolyser systems required for this process are costly, and large-scale manufacturing of these devices is limited at present.

Finally, the challenge of converting or building hydrogen-specific infrastructure ranging from pipelines, storage and refuelling stations will require substantial capital expenditure.

What are compound semiconductors?

The primary purpose of this white paper is to assess the potential of compound semiconductors to be integrated within the green hydrogen ecosystem and identifies opportunities that can make optimal use of such components.

Compound semiconductors are comprised of two or more elements. One of their unique properties is a wide bandgap. The bandgap is the energy required to promote an electron from the valence band to the conduction band in a semiconductor material, allowing it to conduct electricity.

Compound semiconductors have bandgaps greater than 2 electron volts (eV), while traditional semiconductors have bandgaps less than 2 eV. This larger bandgap allows compound semiconductor power devices to operate at higher voltages, temperatures, and frequencies.

Common compound semiconductors include silicon carbide (SiC) and gallium nitride (GaN). Compound semiconductors have many advantages over traditional semiconductors made from silicon (Si), including higher breakdown voltages, operating temperatures, faster switching speeds, and power densities. This makes them ideal for power electronics, lighting, and high-frequency radio-frequency devices semiconductors.

Additionally, compound semiconductors can significantly improve energy efficiency in various applications, including electric vehicles and renewable energy systems.

SiC compound semiconductors offer several advantages over Si, including higher voltage capability, faster-switching speed, lower power losses, enhanced thermal stability, and the ability to operate at high temperatures.

With a bandgap that is up to three times larger and a breakdown voltage that is 10 times higher than that of Si, SiC is well-suited for high-voltage applications ranging from 600 V to over 10 kV, which would not be feasible to achieve efficiently with Si.

SiC diodes were introduced initially in power supplies and photovoltaic (PV) inverters in the 2000s, and then both diodes and metal-oxide-semiconductor field-effect transistors (MOSFETs) proliferated into motor drive, uninterruptible power supply, EV charging infrastructure, rail traction, and wind turbine industries.

As of 2022, industrial and energy markets represent around 40% of the SiC components market, where SiC is expected to show a double-digit compound annual growth rate in each of the markets over the next five years, replacing Si with the added advantage of cost reduction mainly in the high-volume automotive sector.

GaN devices demonstrate remarkable superiority over over Si. With high-speed switching capability, a breakdown voltage that is 3.5 times more robust, and a bandgap that is notably 3.4 times larger, GaN effectively retains functionality even under elevated temperature conditions.

These attributes make GaN devices ideal for designing systems with smaller passive components, i.e. filters (inductors and capacitors) and heatsinks. GaN semiconductors have made their way into a variety of applications, from power devices to RF components, lasers, and photonics, because of their exceptional performance and efficiency.

Gallium arsenide (GaAs) is a compound semiconductor with two elements: gallium and arsenic. It has high electron mobility, suitable for high-frequency transistors.

With a direct bandgap of 1.4 eV and higher breakdown voltage than Si, it is a potential candidate for high-speed electronics, mobile phones, satellite communication, and radar systems.

GaAs has been explored for use in high-efficiency solar cells, light-emitting diodes (LEDs), lasers, and other optoelectronic devices.

Indium gallium arsenide (InGaAs) is another promising compound semiconductor with a wide bandgap. It finds application in optoelectronics, solar cells, thermophotovoltaic (TPV) systems, and high-speed electronic devices.

An important application of InGaAs is in photodetectors and high-speed communication devices such as lasers and photodiodes. They are being explored for single-photon avalanche diodes (SPADs), which can operate in the short-wave infrared (SWIR) range and could be used in hydrogen detection for gas monitoring.

Finally, gallium oxide (Ga_2O_3) is a compound semiconductor with future potential. It has a significantly higher bandgap than Si, SiC, and GaN, of about 4.9 eV, which means that it can operate at even higher voltages and temperatures. It is reportedly more cost-effective than GaN due to its ability to be grown in bulk.

The potential applications are in power conversion, such as in EVs, traction locomotives, industrial drives, etc., and optoelectronics, such as sensors.

While Ga_2O_3 shows potential, it is still a material for the future as some challenges need to be addressed before it becomes mainstream, such as low thermal conductivity and lack of effective and reliable fabrication techniques.

The potential for compound semiconductors for green hydrogen

Over the last five years, CSA Catapult has been actively engaged in high-profile projects with UK companies to utilise compound semiconductors. Harnessing their unique properties to enhance energy efficiency in a range of applications, some of the lessons learnt from these projects can be applied to the green hydrogen.

We have identified several key areas where compound semiconductors can play a significant role in the green hydrogen ecosystem.

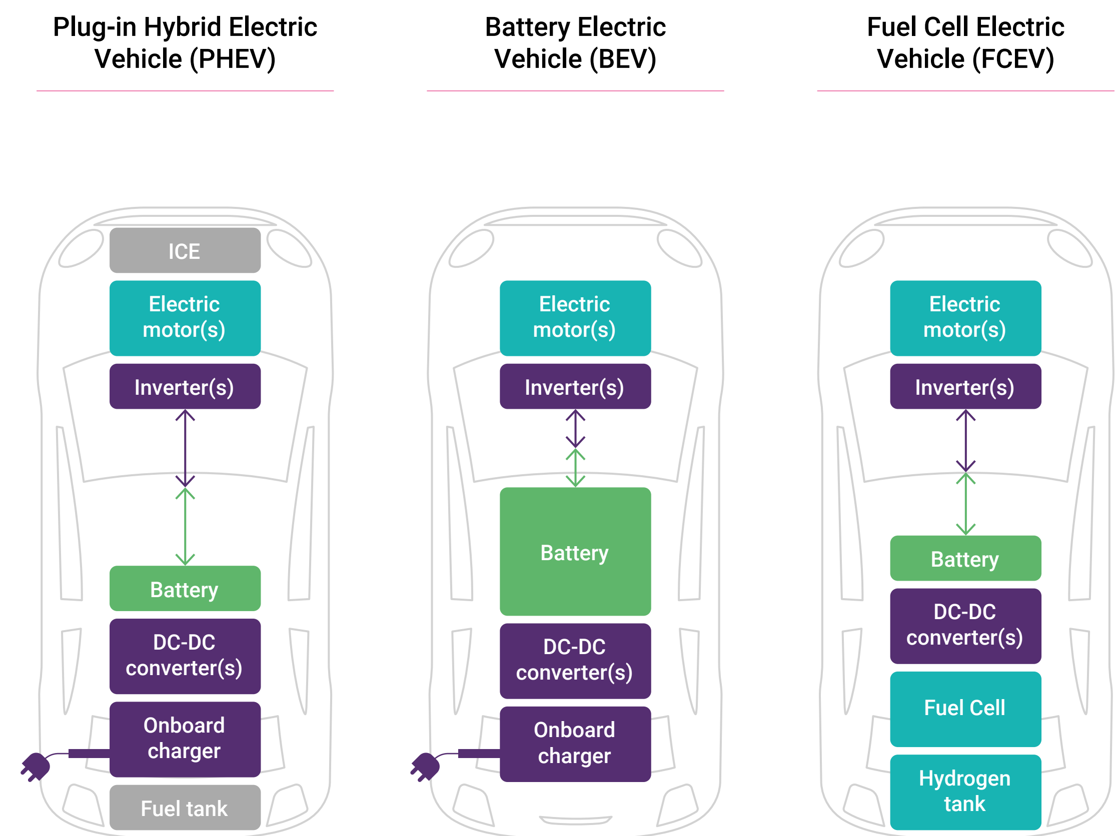
The most critical application being power electronics. This is due to their superior material properties, such as higher power density, faster switching speeds, and reduced power losses compared to traditional silicon-based devices. As a result, they are an ideal choice for a variety of green energy applications, including electric vehicles, renewable energy systems, and power grids.

Additionally, compound semiconductors can enhance the performance of energy storage systems, industrial applications, and smart grids. Thus, compound semiconductors will play an important role in transitioning towards a more sustainable energy system.

Power electronics in hydrogen fuel cell vehicles

Power electronics applications within hydrogen-based transportation fall into two groups: fuel cell electric vehicles (FCEVs) and other applications, including aviation, marine, and railway. Such systems are essential for improving the efficiency and performance of all transportation applications.

FCEVs and selected power electronics solutions have high potential demand right now. By contrast, other transportation methods, such as aviation, marine, and railway, may take longer to become commercially viable due to various factors, including technology maturity, regulatory hurdles, and infrastructure limitations.



Power train comparison of PHEV, BEV and FCEV
(Source: APC)

The illustration above maps out the different power train architectures of plug-in hybrid-electric vehicles (PHEV), battery electric vehicles (BEV) and FCEV. PHEVs combine a conventional internal combustion engine with an electric motor and a rechargeable battery. They can operate on electric-only mode for short distances and switch to the combustion engine for longer trips.

BEVs are entirely electric, powered by a rechargeable battery driving an electric motor. They produce zero tailpipe emissions and typically have lower operating costs due to reduced maintenance and fuel expenses. However, BEVs are limited by their driving range, which is often shorter than that of PHEVs and FCEVs, and longer charging times compared to refuelling traditional vehicles or FCEVs. Typically, it takes 30 to 45 minutes on a rapid EV charger and upwards of four hours on a slow charger to achieve an 80% charge.

FCEVs use hydrogen fuel cells to generate electricity for the vehicle's electric motor. They also have a smaller battery in the powertrain. They require much less refuelling time, usually only a few minutes, and longer driving ranges compared to BEVs. Additionally, FCEVs emit only water vapour and are considered to be environmentally friendly. As the demand for sustainable and clean transportation options grows, FCEVs are poised to play a vital role in the transition to a zero-emission future.

Two distinct powertrains

While some power electronic solutions developed for BEVs can be adapted for use in FCEVs, it is not a direct plug-and-play process. The power electronics must be specifically designed and tested for use in fuel cell systems to ensure optimal performance and reliability. This is precisely an area where the CSA Catapult's expertise can add value. It can also demonstrate that compound semiconductors are key for the successful deployment of systems adopting hydrogen fuel cells.

In both cases, the performance of these power electronics components can significantly affect the efficiency, reliability, and overall performance of the FCEV powertrain. Therefore, advanced power electronics technologies, such as compound semiconductors, are often used in these applications due to their superior efficiency and ability to operate at high frequencies, temperatures, and voltages.

These developments underscore the increasingly critical role of SiC-based technology in the field of FCEVs and sustainable energy solutions. The deployment of SiC in FCEVs, whether in booster power modules, air compressors, or metal-oxide-semiconductor field-effect transistor (MOSFET) modules, brings several benefits, such as higher power density, faster switching speeds, and reduced power losses compared to Si devices. As such, the rise of SiC technology shows promise for driving further advancements in the FCEV market, supporting the broader transition towards a more sustainable energy ecosystem.

In addition, there are numerous instances where OEMs and other relevant stakeholders are actively investigating the possibility of incorporating fuel-cell technologies. This presents significant opportunities to use compound semiconductors.

While there are many positive benefits of hydrogen, the uptake of FCEV passenger cars has been limited to date, because of the high cost of vehicles and the lack of public refuelling stations.

In 2020, there were approximately 1,300 FCEVs on the road in Europe. However, market forecasts suggest that this number could exceed four million units by 2030. Notably, Asia is expected to emerge as the primary region for FCEVs, with an estimated 5.1 million vehicles projected by 2030 due to factors such as government policies, investments in infrastructure, market demand and industry commitment.

Hydrogen fuel cells, though less popular than lithium-ion batteries in light transport, may find a niche in long-haul, heavy-load transportation due to their potential for longer range and less weight. Looking at the recent projects in the UK, there appears to be a greater focus on looking to produce hydrogen-propelled commercial vehicles over passenger cars.

UK built hydrogen electric HGV prototype
(Source: Tevva)

Worldwide, numerous commercialisation efforts for FCEVs are underway, with OEMs like Volvo, Geely, and Nikola actively investigating hydrogen as a fuel source to achieve a Net Zero future.

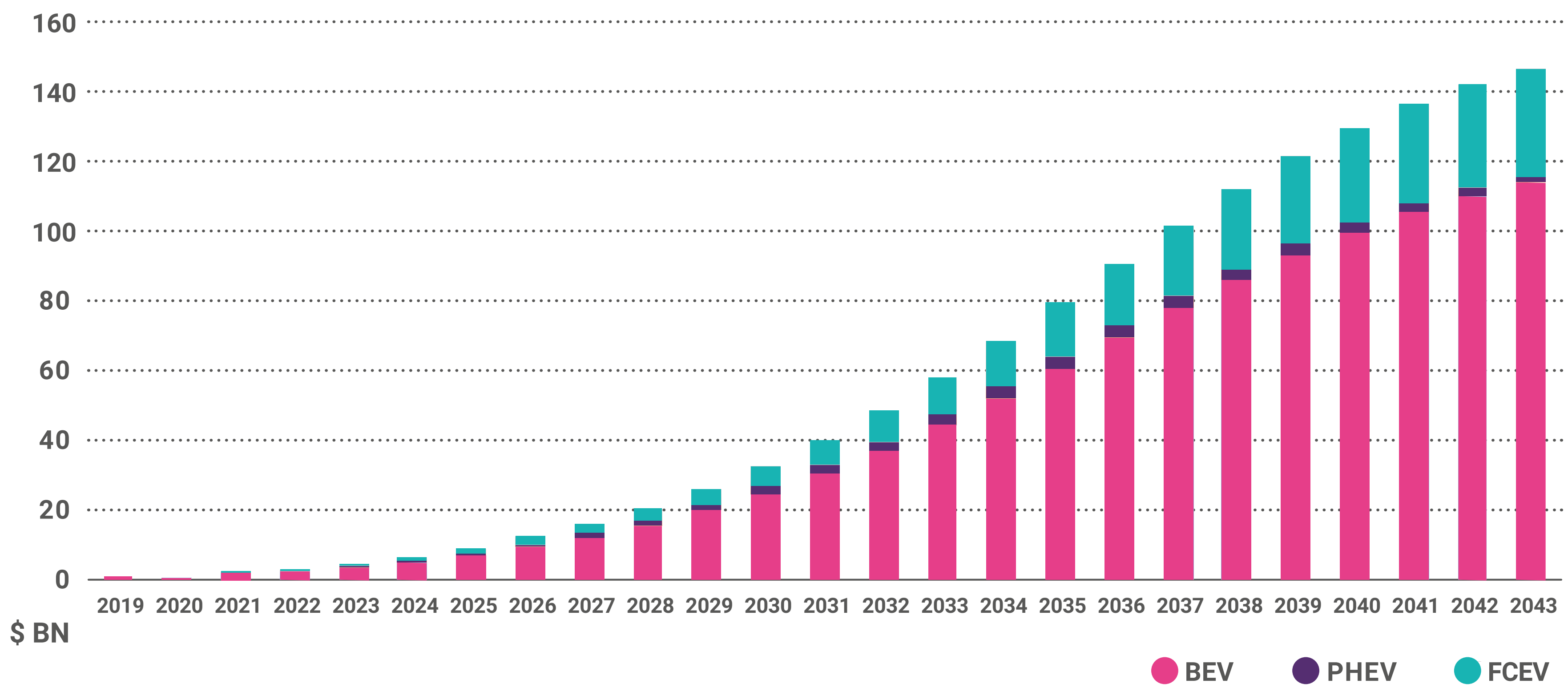
Fuel cell technology holds significant promise in the heavy-duty truck sector, primarily due to its ability to meet the demanding duty cycle requirements and provide sufficient range.

Looking at the forecast data in the following charts, the consensus from both industry analysts and leading research technology organisations such as the APC, suggest that fuel cell technologies are more likely to be adopted for mass market applications from 2030 onwards.

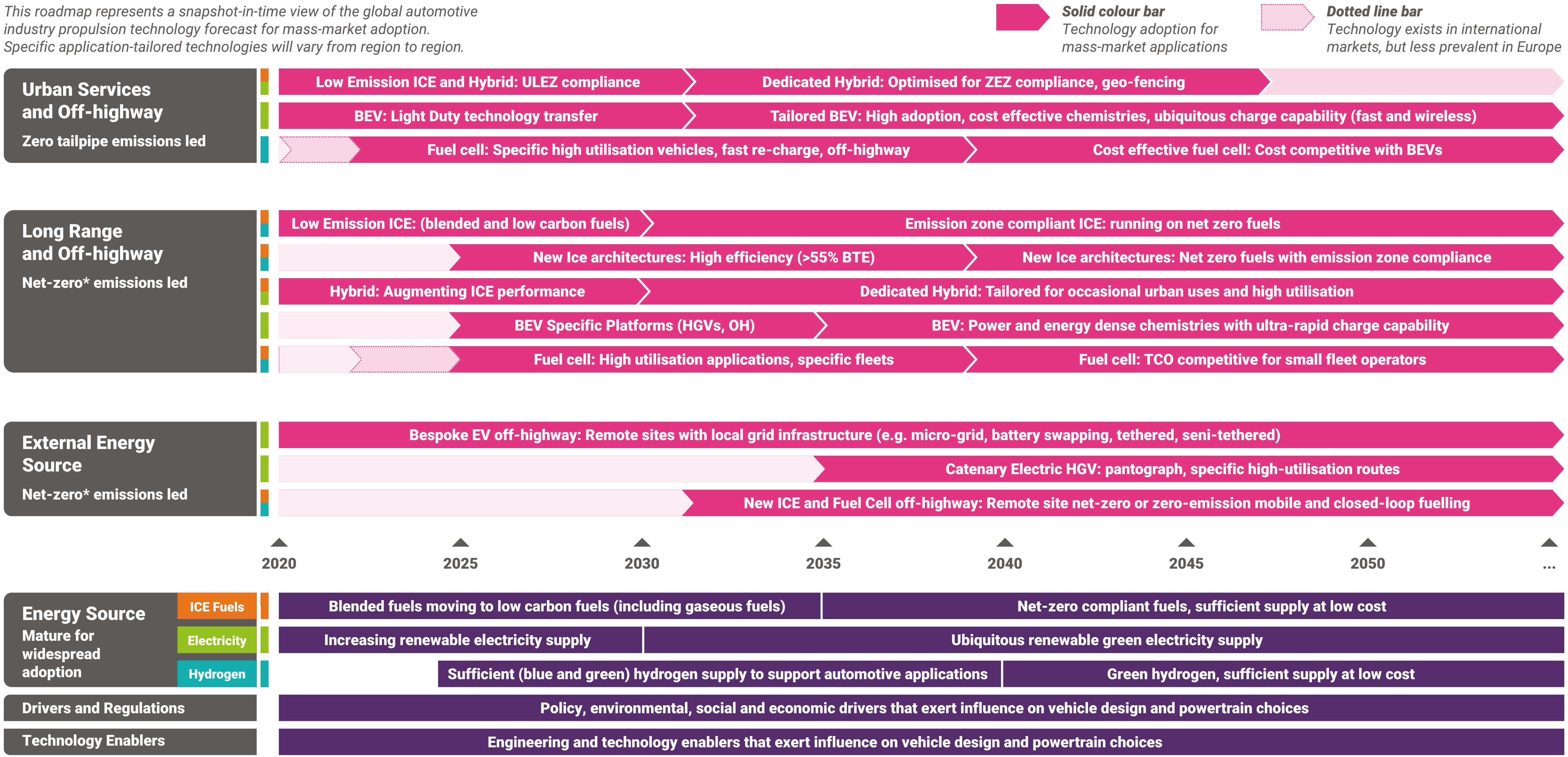
There are multiple challenges to take into consideration, such as the uptake of BEV-based heavy-duty trucks in the coming years to replace ICE vehicles. Industry analysts IDTechEx predict that in 2043, while FCEV will account for 21.1% of HGVs on the road, nearly 78% of all heavy-duty trucks will be BEV-based. PHEV-based HGVs make up the remaining 1.2% of the total addressable market (TAM).

Upon further examination of APC's future vehicle roadmap, the viewpoint is more optimistic for hydrogen-fueled HGVs. It is encouraging to see that the APC estimates the deployment of FCEVs from 2025 for long-range HGVs. However, on the proposed timeline the cost parity for green hydrogen to go mass market for FCEVs is estimated to be in 2040, whereas the infrastructure to supply sufficient renewable green electricity for BEV-based HGVs has the potential to be in place a decade earlier.

Heavy-duty truck market forecast 2019-2043 ($ BN)



The global forecast for zero emission HGVs
(Source: IDTechEx)



Hybrids = Mild, HEV, PHEV and range extender

Heavy goods and off-highway vehicle roadmap
(Source: APC)

Challenges for FCEV to become a viable alternative

For green hydrogen to be considered a viable fuel for haulage companies and public transport there are multiple challenges ranging from the total cost of ownership (TCO) and the ability to refuel fleets of FCEV HGVs both UK-based and for those visiting from the EU.

This table illustrates the different running costs of all variants of HGVs, taking into account the fluctuations in the cost of fuel or energy using three different scenarios over a five-year period, which is the normal depreciable life of a truck.

	PRICE SCENARIO	PRICE	UNITS	FUEL CONSUMPTION	UNITS	100,000 KM H_2 PRICE P.A. ($ 000)	FIVE-YEAR H_2 FUEL PRICE ($ 000)
FCEV	Low	5	$/kg H^2	6.7	kg H^2/100 km	$33.3	$167
	Medium	7.5	$/kg H^2	8.1	kg H^2/100 km	$60.4	$302
	High	10	$/kg H^2	9.4	kg H^2/100 km	$94.3	$471
H2 ICE	Low	5	$/kg H^2	7.0	kg H^2/100 km	$35.0	$175
	Medium	7.5	$/kg H^2	8.5	kg H^2/100 km	$63.4	$317
	High	10	$/kg H^2	9.9	kg H^2/100 km	$99.0	$495
BEV	Low	0.1	$/kWh	1.0	kWh/km	$10	$50
	Medium	0.15	$/kWh	1.5	kWh/km	$22.5	$113
	High	0.27	$/kWh	2.0	kWh/km	$54.0	$270
Diesel	Low	0.9	$/L	7.3	mpg	$29.9	$150
	Medium	1.2	$/L	7.3	mpg	$38.8	$194
	High	1.5	$/L	7.3	mpg	$48.5	$243

Total cost of ownership compared between fuel types of HGV
(Source: IDTechEx)

The cost model suggests that for hydrogen to become successful for long-range haulage, the at-pump price will have to be less than $5.5 per kg, to be competitive with the equivalent diesel HGV.

Compound semiconductors are expected to enhance FCEV technology and market development. The superior performance of compound semiconductors will enable the creation of smaller, lighter components and enhance vehicle performance. Studies are currently being conducted on the utilisation of compound semiconductors in FCEVs, and further research in this domain is expected to continue in the future.

As the technology matures, compound semiconductors are expected to become more cost-effective, thereby reducing the overall cost of FCEVs, a crucial factor for market adoption.

Aviation

Hydrogen can be used as a fuel for fuel cells or as a direct combustion fuel in aircraft engines. Fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, which can then be used to power electric motors.

Compound semiconductors can be utilised in the power electronics and control systems of hydrogen-powered aircraft, enhancing the efficiency and performance of these systems. Additionally, hydrogen storage and distribution systems can benefit from the increased efficiency and high-temperature operation capabilities of compound semiconductors.

Superconductivity for aircraft represents a cutting-edge concept within the aviation industry, in which the propulsion systems employ superconducting technology, specifically superconducting motors. These innovative motors utilise materials capable of conducting electricity without resistance when cooled to exceedingly low temperatures. As a result, they exhibit markedly improved efficiency and power density compared to their traditional electric motor counterparts.

Although the development of superconductivity for aircraft is still in its infancy, it holds considerable promise for significantly reducing fuel consumption, emissions, and noise levels, thereby contributing to worldwide decarbonisation efforts. As mentioned, these motors are driven by electricity, which can come from various sources, including fuel cells.

Hybrid-hydrogen plane
(Source: ZeroAvia)

Traditional 'tube and wing' aircraft configurations offer limited scope for achieving these ambitious targets through incremental improvements. Conversely, Distributed Propulsion (DP) represents a revolutionary approach that expands the design possibilities for aircraft, thereby enabling substantial reductions in fuel consumption, emissions, and noise.

The Advanced Superconducting Motor Experimental Demonstrator (ASuMED) project has successfully developed the world's first complete superconducting motor prototype, capable of meeting the power densities and efficiencies required for hybrid-electric distributed propulsion in future large civil aircraft. This accomplishment paves the way for achieving the stringent targets stipulated in the Flightpath 2050.

Moreover, compound semiconductors might enhance the performance of cooling systems in superconducting devices. For example, they could be employed in the power converters and inverters that operate cryocoolers (the cooling devices used for superconductors), potentially enhancing their efficiency and decreasing their size.

Marine

In the marine sector, hydrogen can be used in fuel cells to power electric motors or directly in internal combustion engines. First-generation vessels are coming on stream and compound semiconductors have the potential to play a crucial role in the power electronics and control systems of future hydrogen-powered ships. For example, SiC and GaN semiconductors can be employed in power converters and inverters for fuel cell systems, improving efficiency and reliability.

Moreover, compound semiconductors can be used in hydrogen generation, storage, and distribution systems on board ships. Several projects have begun to investigate the use of fuel cells for marine applications.

- **HySeas III:** A car and passenger ferry powered by hydrogen fuel cells. The fuel cells will be combined with a battery-electric drivetrain, and the hydrogen will be produced from renewable electricity.
- **3MW Marine:** Design of a multi-parallel fuel cell system. The project encompasses highly redundant end-to-end whole-ship energy efficiency design and integration. Enabled by novel motors, drives, and power electronics, the fuel cell system will deliver more than 3 MW (megawatts) of power.

Rail

Hydrogen fuel cells can be used as an alternative power source for trains, replacing diesel engines or even complementing electric systems. Compound semiconductors can improve the efficiency of power electronics and control systems in hydrogen-powered trains, such as those found in power converters, inverters, and motor drives. As with aviation and marine applications, compound semiconductors can also be employed in hydrogen storage and distribution systems.

The HydroFLEX initiative represents a pioneering collaboration between the Birmingham Centre for Railway Research and Education at the University of Birmingham and Porterbrook, a railway rolling stock company.

The project's objective is to showcase how hydrogen can be integrated across the rail network as a cleaner substitute for current diesel-powered trains. The project focuses on the modification of a pre-existing Class 319001 train by equipping it with a hydrogen fuel cell. This transformation enables the train to operate independently on hydrogen power on non-electrified routes.

HydroFLEX hydrogen fuel cell train
(Source: University of Birmingham)

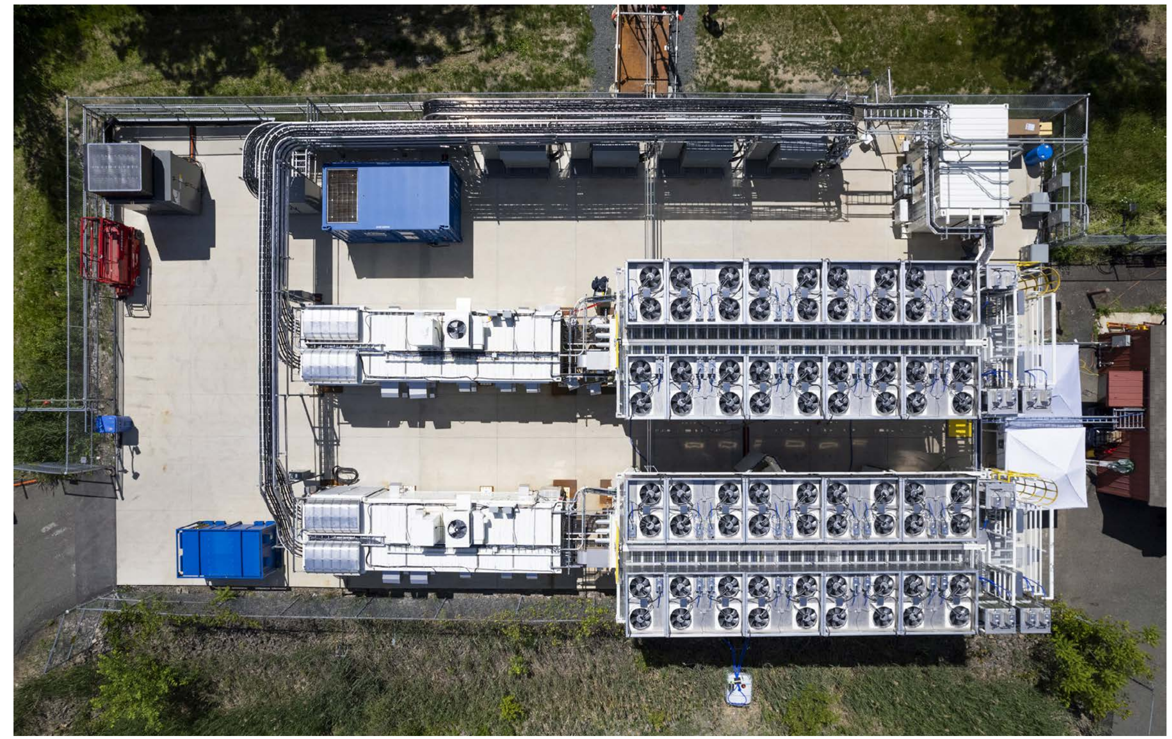
Microgrids

Microgrids are small-scale power grids that can operate independently or in collaboration with the main grid. These localised stations have their own power resources, generation, and loads, allowing them to disconnect from the conventional grid for short durations (or during blackout events), and operate autonomously, improving grid reliability and security.

Hydrogen microgrids utilise fuel cells for power generation. The fuel cells convert the chemical energy of hydrogen and oxygen directly into electrical energy, producing only water vapour as a by-product. As a result, these microgrids offer clean, reliable power, making them ideal for critical facilities like hospitals, data centres, and military bases that require an uninterruptible power supply (UPS).

Data centres are an important application for microgrids due to their high, continuous power demand. Ensuring a reliable, uninterrupted service is crucial, as disruptions can lead to severe consequences like data loss or system failures.

Technology companies such as Microsoft have been exploring ways to boost the reliability and sustainability of their data centres. One method is the use of hydrogen fuel cells.



Hydrogen fuel cell powered data centre
(Source: Microsoft)

Wind

Modern offshore wind farms, incorporating turbines of significant size, are designed to capture and convert vast amounts of wind energy. The electricity generated by the wind turbine is typically in the form of variable frequency alternating current (AC). This must be converted into direct current (DC) using a device known as a rectifier or converter.

The scale and technology inherent in these systems also diverge greatly from the traditional windmills of the past. Given the substantial energy output of these turbines, their operational efficiency and dependability become critical factors. Any inefficiencies or failures in the system can lead to considerable energy and economic deficits.

The integration of SiC technology in wind turbines has the potential to enhance their operational efficiency and reliability. This advancement can result in a reduction of costs and an increase in the production of usable energy.

This could result in either a reduction in the number of wind turbines or a decrease in their size while maintaining the same energy yield.

Wind power systems need to successfully harness the energy of the wind with as few power losses as possible. So these metrics are critical to optimise the performance of a hydrogen electrolyser that is linked to the wind farm.

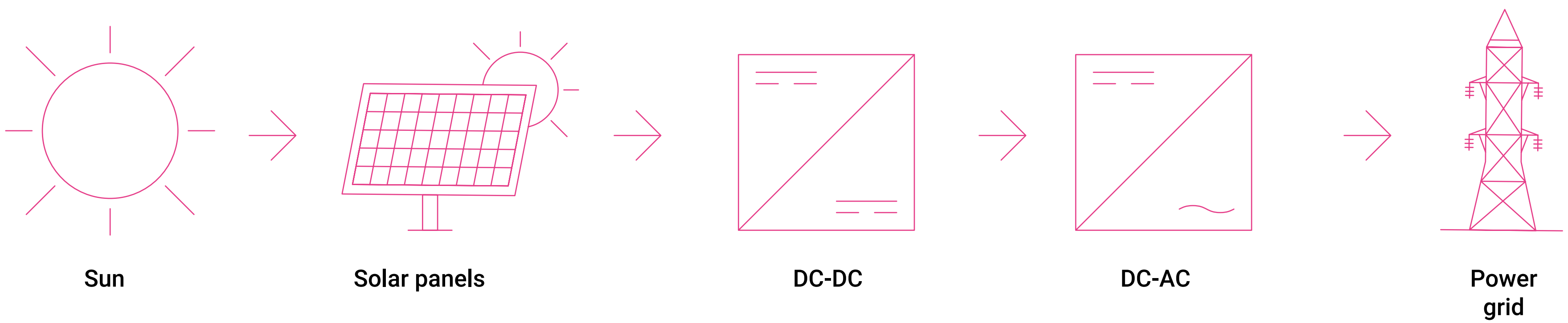
SiC’s resilience to high temperatures and voltages may also lead to a decrease in maintenance downtime and system failures, ensuring a consistent energy output.

Solar

Solar power, with its affordability, widespread availability, and continuously improving efficiency, is experiencing rapid growth as a renewable energy choice for residential, commercial, industrial, and utility-scale purposes.

Modern photovoltaic (PV) systems utilise advanced solar panels to capture sunlight and convert it into usable electrical energy. To maximise the energy output and overall performance of these systems, efficient power conversion is crucial. Compound semiconductors, such as SiC, outperform traditional silicon-based materials in power electronics applications.

The exceptional characteristics of SiC in solar implementations result in minimised energy wastage and enhanced efficiency within PV systems. Also, because compound semiconductors are effective at heat dissipation, SiC technology helps enhance the reliability and lifespan of PV installations.



Solar photovoltaic power generation

Electrolysis

Electrolysis is a process that uses DC electrical energy to drive a non-spontaneous chemical reaction. A common application of electrolysis is the splitting of water into hydrogen and oxygen gases, which is of particular interest in the production of green hydrogen for use as a clean energy source. The DC power used in electrolysis is precisely controlled to ensure efficiency. The control and conversion of this power are facilitated by power electronics.

Power electronics are essential in electrolysis because they allow for the efficient conversion and regulation of electric power. As discussed in the section of the report on wind power, the AC supplied by power grids must be converted into DC for the electrolysis process, a process known as rectification or AC-DC conversion.

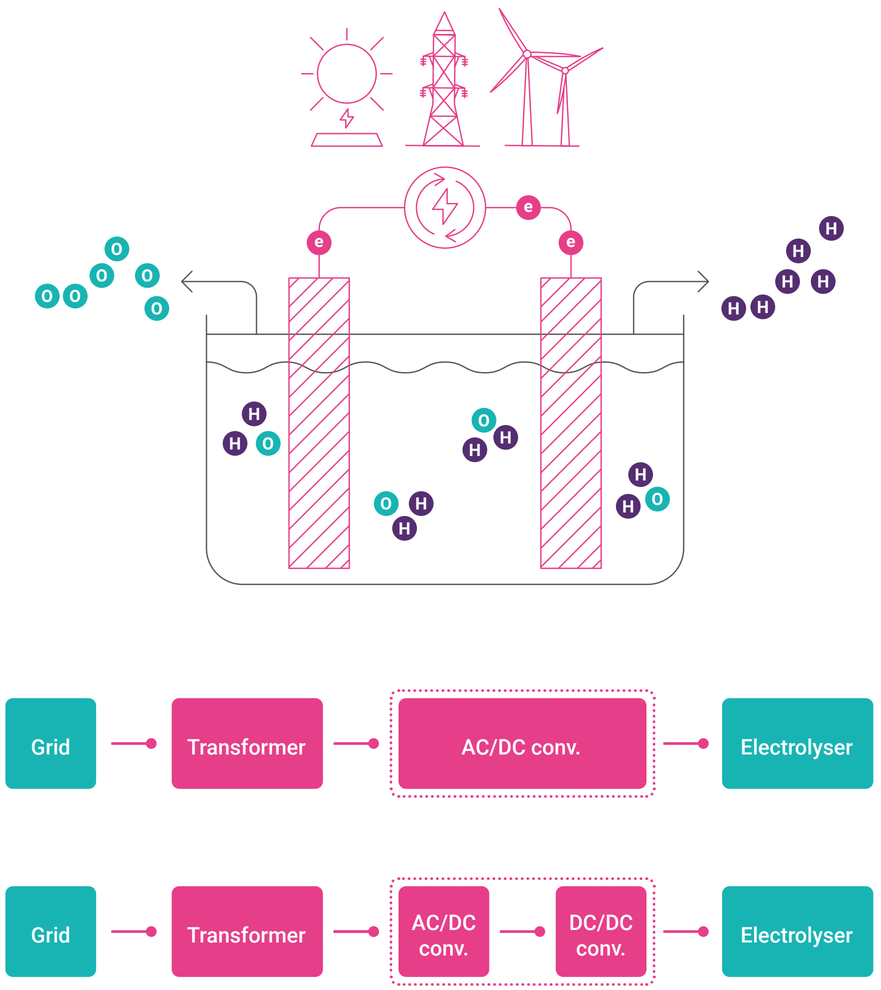
High-power semiconductors are used in this conversion, and the quality of these components can significantly influence the efficiency of the process. The introduction of compound semiconductor-based power electronics can minimise losses and inefficiencies, contributing to an effective and reliable electrolysis system.

The graphic shows a simplified process for power supply for electrolysers. The single-stage solution only requires AC/DC converter, while the two-stage solution involves both AC/DC converter and DC/DC converter. Semiconductors are imperative for efficient converters.

It is clear that power electronics are critically important for electrolysis to achieve higher performance and reduce waste. According to CSA Catapult's head of Power Electronics, Dr Ingo Lüdke, the use of modular system inverters could potentially serve as a pathway to enhance the efficiency of electrolysers, especially as production scales up.

However, it is worth noting that this area might be considered specialised since the primary focus currently lies on the design aspect of electrolysers. There is a clear need for more comprehensive research in this area.

The broader application and commercialisation of compound semiconductors in electrolysis still have considerable ground to cover. This indicates that while there are promising developments, the journey towards mainstream adoption is ongoing, requiring further R&D and innovation.



Single-stage solution and two-stage solution power supply for electrolyser
(Source: ABB)

Single photon avalanche diodes (SPADs)

SPADs have emerged as a promising technology for gas sensing applications, and researchers have been exploring their potential in various areas. One area of interest is the use of indium gallium arsenide (InGaAs) SPADs for sensing hydrogen leakage during storage and transportation.

As a compound semiconductor, InGaAs SPADs offer unique advantages in gas sensing applications. Their sensitivity to near-infrared light, combined with their ability to detect single photons, makes them well-suited for detecting and quantifying gas emissions. CSA Catapult also has been working on groundbreaking gas sensing technology utilising SPADs for greenhouse gas detection.

The utilisation of InGaAs SPADs in hydrogen leakage detection is of particular interest due to the flammability and safety concerns associated with hydrogen. Accurate and timely detection of hydrogen leaks is crucial to ensure the safe handling and transportation of this potentially volatile gas.

It is worth mentioning that the advancement and adoption of SPADs for hydrogen detection will depend on factors such as cost-effectiveness, scalability, and the ability to meet stringent safety requirements. Ongoing research efforts aim to address these challenges and explore the full potential of SPADs in gas sensing applications, including the detection of hydrogen leaks.

While SPADs have not yet reached widespread use specifically for hydrogen detection, they remain a promising technology that could contribute to enhancing safety measures in the storage and transportation of hydrogen in the future.

Conclusion

Hydrogen is considered a crucial element in decarbonising the UK industry, promoting clean growth, and enhancing our long-term energy security. The UK government's Ten Point Plan for a Green Industrial Revolution has set a target of 10 GW of low-carbon hydrogen production capacity by 2030 for use across the economy, as outlined in the UK Hydrogen Strategy.

There are many challenges and constraints associated with the adoption of compound semiconductors to help hit this target, such as higher costs of production than silicon, limited availability of materials, technical expertise requirements, and the lack of compatibility with existing infrastructure.

This is the long-term goal of CSA Catapult to help industry to make compound semiconductors more mainstream in the coming years, by addressing these challenges head-on and continuing R&D to fully unlock the potential of compound semiconductors in the future production of green hydrogen in the UK.

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