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Review

Fuel cell development for New Energy Vehicles (NEVs) and clean air in China

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ABSTRACT

This paper reviews the background to New Energy Vehicles (NEV) policies in China, and the key scientific and market challenges that need to be addressed to accelerate fuel cells (FCs) in the rapidly developing NEV market. The global significance of the Chinese market, key players, core FC technologies and future research priorities are discussed.

1. Introduction

China became the largest car producer a decade ago, set to overtake the USA as the world's biggest oil importer in 2017. New passenger vehicle sales in China will exceed 25 million per annum in 2017 [1]; in September 2017 alone, sales of vehicles in China reached 2,709,000 units, up 5.7% year on September 2016. Increased vehicle production and sales meet exponential growth expectations within the car industry, but the increased emissions from road transport will also have well-quantified impacts on urban air quality and greenhouse gas (GHG) emissions in China [2]. Traffic emissions have become incompatible with Chinese policies on climate change and the protection of human health. This unsustainable model results in real world emissions higher than the regulated emission factors [3], high energy usage and low utilization [4], exacerbating air quality problems in cities like Beijing. Urban air pollution has significant consequence for human health today; in 2013 premature deaths due to air pollution cost the global economy an estimated $225 billion in lost labour income, and $5.11 trillion in welfare losses worldwide, equivalent to the gross domestic product of India, Canada, and Mexico combined [5]. China alone lost ~ 10% of its GDP in 2013 as a result of air pollution according to this World Bank study. If car ownership follows the Western model, there will be 10 billion cars in China by 2100 [6].

Environmental protection and economic growth ambitions have promoted the electrification of urban transport in China, attempting to de-couple transport from urban emissions. Since the 2000s, the Chinese Government championed a national strategy for clean vehicles that is distinct from the Western model, primarily to address urban pollution [7]. At the same time, around the world, fossil fuels are increasingly seen as an investment liability, prompting significant investment shifts into decarbonised clean energy. Several national and local policies in China encouraged the development of New Energy Vehicles (NEVs) which are based on battery technologies, and other non-combustion technologies such as fuel cells (FCs), which can improve battery performance and lifetimes [8]. NEVs are essential for China to meet international climate change obligations GHG emission reduction targets, which are reviewed every 5 years under the United Nations Framework Convention on Climate Change [9]. As a result, Chinese incentives for FC vehicles (FCVs) currently extend beyond those offered for battery NEVs.

This paper reviews the background to NEV policies, and the key scientific and market challenges that need to be addressed to accelerate FCs in the rapidly developing NEV market. The global significance of the Chinese market, key players, core FC technologies and future research priorities are discussed.

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2. Clean air in China: an environmental imperative

Renewable clean energy for vehicles and other applications is already growing faster in many developing nations than in richer countries because it is economically and environmentally rational [10]. The aggregate consequences of fossil fuel emissions impact in two ways; (1) poor air quality in cities inflicts ill-health on billions of urban residents around the world, and (2) worsens climate change [2]. Transport contributes around a quarter of global GHG emissions, and substantially more to urban air pollution. While air pollution from heavy industry remains significant in China, the impacts of these sources are being steadily reduced in cities, while traffic related pollution is increasing. According to the World Bank, the growing global burden of disease attributable to air pollution from vehicles, exceeded those from diseases such as HIV, tuberculosis, or malaria, making it the largest environmental public health risk by 2014 [11]. Motorized road transport resulted in more than 1.5 million deaths and 79.6 million healthy years of life lost annually.

Key trends in air pollution collated by the World Health Organisation (WHO) between 2008 and 2013, showed that global urban air pollution levels rose by 8%, and in general, air pollution levels were lowest in high-income countries (Fig. 1; [12]). Strategies to reduce air pollution (largely from poor quality coal) were enacted successfully in Europe and North America since the 1950s [4]. Transport policy interventions evolved more recently to address vehicle emissions, after vehicles re-introduced combustion into cities, having been banished under the Clean Air Acts of the 1960s when domestic heating was centralised to rural power stations. Interventions include reducing travel distances by improved city planning, increasing public transport provision, congestion charging in city centres and shifting road freight to rail and shipping, with plans for banning combustion (petrol and diesel) vehicles in many European cities by 2040. However, even with traffic intervention policies, urban air pollution continues to affect billions of people; by 2016, 92% of the world population lived in areas that exceeded the WHO air quality standards [13]. This rise in urban air pollution demonstrates the difficulty in offsetting growing vehicle numbers by slowly reducing individual emission factors.

The UN Conference of Parties (COP21) Paris agreement in December 2015 provided the regulatory basis for global economic movement away from fossil fuels towards low carbon technologies [9]. Governments including China agreed to achieve GHG emission reductions limiting modelled global average temperature rises to less than 2 °C, and prevent dangerous climate change scenarios [10]. However, while studies have shown that EVs reduced local air pollution by replacing conventional cars, GHG emissions could only be reduced by ~ 30% in China where coal is used for electricity production [14]. Accelerating cleaner NEV deployment is therefore critical to decarbonise transport in China, by promoting low-carbon fuels, electrification and clean technology development. Since the trend in aggregate emissions remains upwards, drastic cuts in emissions are now required. COP21 led to recent announcements in the UK and other developed countries to ban fossil fuel powered vehicles in cities by 2040, and China is set to follow in 2018. Global investors increasingly see fossil fuels as an investment portfolio risk, which shunts investment capital from fossil fuels towards clean energy. This influx of so-called patient capital towards clean tech will create massive research and business opportunities in the transport sector, with the NEV programme set to deliver these to the Chinese and global market.

3. Unique conditions for clean vehicle development in China

Electrification of energy is increasing across the globe [10,15] and offers nations an opportunity to cut their GHG emissions; 23% of energy-related GHG emissions worldwide are attributable to transport [16]. Due to scaled infrastructure investments, the internal market in China is rapidly moving energy generation away from fossil fuels to clean technologies, e.g. solar photovoltaics (PV). NEV uptake in China signals battery electric vehicles (BEVs) are displacing fossil fuel vehicles now, but regulators remain encouraging to other technologies such as fuel cells (FCs), which can decarbonise emissions further. China has been the largest producer of NEVs since 2015 and has determined that 8% of cars sold in 2019 are powered by "new energy", 12% by 2020 [7]. China already leads the world in solar PV and battery production [10,17], and is rapidly internationalising NEV production capacity and sales reach, engaging and buying assets in the sector. FC technology enables batteries and vehicle electrification, by extending range and delaying the need for prolonged re-charge times; one typical FC model is depicted in Fig. 2 as an example. As a result, these economic, social and environmental factors are propelling China to leapfrog countries like Germany and the UK where early electric and hydrogen vehicle fleets were introduced, but not fully commercialised due to failure to prioritise zero emission vehicles [18]. Other national policies align, with NEVs hailed as benefiting citizens and communities and a logical

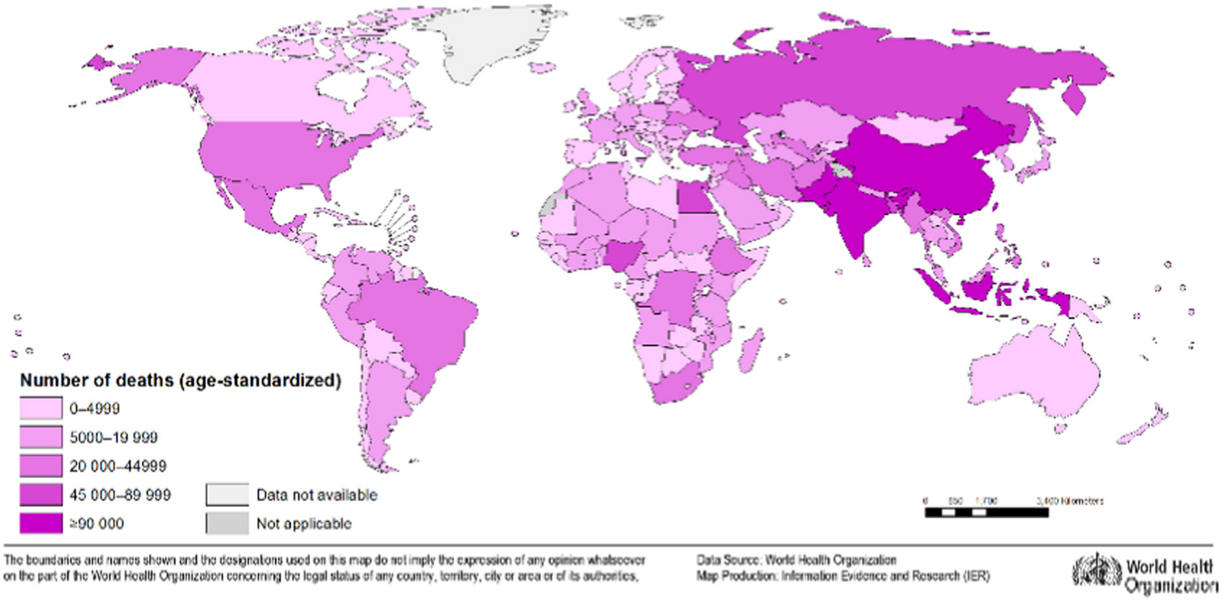


Fig. 1. The distribution of deaths attributable to ambient air pollution globally, age standardised, 2012, as modelled by the World Health Organisation (WHO). [12]. [Permission requested].

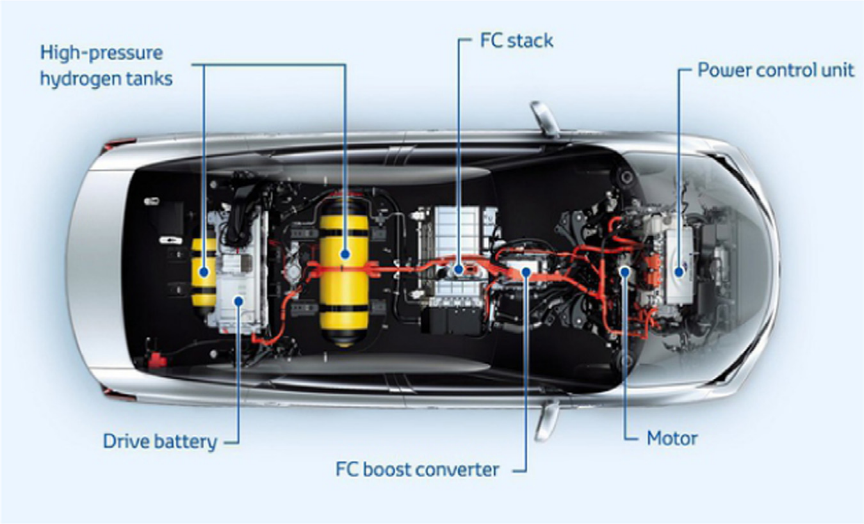


Fig. 2. Schematic of the Toyota fuel cell vehicle (FCV).

fit for the socio-politico-economic goal for Chinese citizens. Air quality security achieved through reduced air pollution from NEVs – along with other socio-economic, environmental and food securities – is the goal.

The technical outcomes of the NEV strategy are also aligned with other policies with industry seen as the foundation of economic development. In particular, NEV policies are strategically aligned with *Made in China 2025* which aims to elevate Chinese enterprises from system integrators of components from the West (normally by imitation) who then develop solutions that achieve reasonable performance at the lowest prices, to global innovation leaders that shape industry. The latest Communist Party Conference (CPC) 5 year plan emerging from the 19th CPC meeting in Beijing (October 2017) directed Chinese businesses to focus on smart, green manufacturing. The aim is for China to move up the manufacturing value chain through innovation research and development (R&D) and intellectual property (IP) development. Simultaneously, the UK, USA and Germany are exploring cooperation models to commercialise valuable R&D bases in clean energy technologies by scaling manufacturing, similar to PV [10]. Increasing the NEV manufacturing capacity in China aims to unlock clean vehicle markets by reducing costs, as was demonstrated in the PV market.

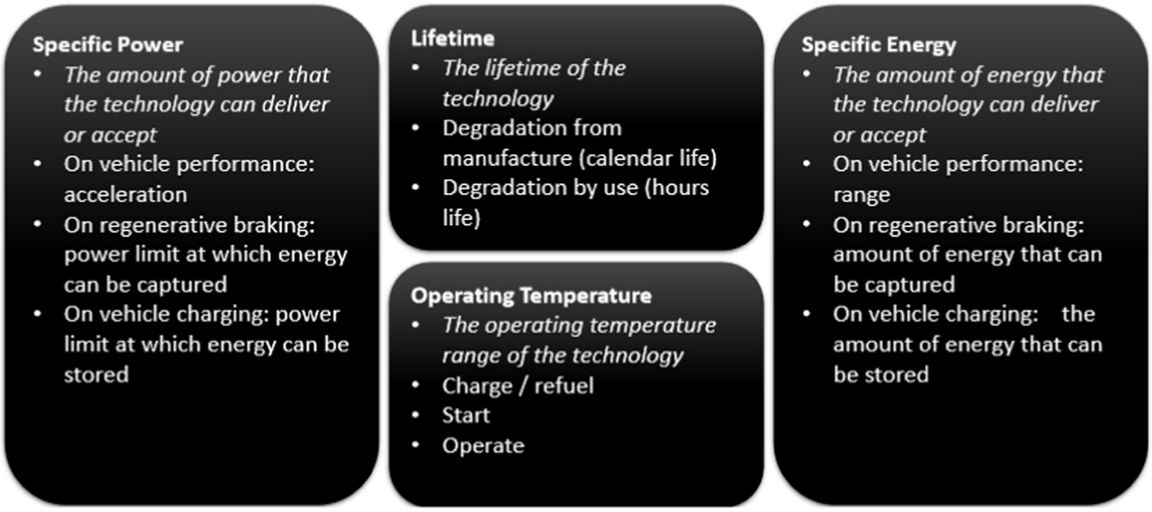
China dominates the PV market, both as a manufacturer and deployer [10,19]. The industry is worth an estimated $100 billion globally and is expected to rise 13% annually. In 2016, China was responsible for around half of the global PV capacity, and it doubled the size of its domestic industry. There are many lessons from the PV and battery industries which benefitted from manufacturing capability being built up to produce small systems [10]. The German feed-in tariff vitally encouraged roof-top PV in the early 1990s, when proliferation proved so popular that PV demand could not be met by local producers, and China was paid to produce systems. The introduction of similar policies in the UK, Italy and Spain demonstrated the scalability of the EU market to Chinese manufacturers. China's expanding manufacturing capacity made steady improvements despite unstable markets and slim margins. As global PV prices plummeted, national demand expanded in China; regional governments offered local incentive schemes, lowering prices further.

Aside from moving from coal to PV, China already pioneered technology interventions to tackle pollution. China undertook nationwide programmes to reduce the impacts of biomass burning (including air pollution), including several aimed at household stoves [20]. In the 1980s, the Chinese government financed the National Improved Stove Program (NISP), to provide rural households with more-efficient biomass stoves and, later, improved coal stoves, for cooking and heating. The Ministry of Agriculture (MOA) ran the NISP: By the early 1990s, NISP had installed 130 million improved stoves, and MOA supported stove manufacturers and energy service companies to standardize stoves. MOA claimed that, in 1998, 185 million of China's 236 million rural households had improved biomass or coal stoves and the health impacts were assessed [20]. Later evaluations demonstrated poor field performance however, and the strategic objectives of eliminating air pollution were not reached [21]. Reviewing this experience, there is a clear need for independent oversight of implementation, quality control and support during the enactment and enforcement of any clean air strategy. In cities, China has displaced combustion bikes with electric bicycles. 200 million battery electric bikes exist in China, with hundreds of manufacturers making > 30 million annually [22]. The penetration of electric bikes into Chinese markets is around 95% electric compared to 5% combustion in Shanghai.

4. New energy vehicles (NEVs) in China: electrified vehicles

As PV demonstrated, the Chinese market offers early scaling opportunities for NEVs since only 0.2% of all passenger vehicles globally (approximately 2 million) were electric in 2016 [23]. National policies in China established support for NEV manufacturing capability expansion and deployment [24]. The Chinese government promoted various plans since 2000 with the goal of leading NEV production by 2012, to create industries, jobs and exports, reduce urban pollution and reduce fossil fuel dependence. NEVs include battery electric vehicles (BEVs) and FC hybrid vehicles (FCVs), but hybrid combustion-electric vehicles (HVs) and BEVs dominate. The key parameters in choosing an on-board vehicle power source (Fig. 3) are strongly dictated by vehicle model. The commercial competition between companies and nations is complex, but the core NEV technologies predicted for long term development are batteries and FCs. If China bans fossil fuel combustion engines in cities in line with Europe, NEVs will still require massive investment in materials R&D, manufacturing infrastructure and charging/refuelling infrastructure.

Battery technologies have already benefitted from scaled mass manufacture, which built manufacturing capability, extensive customer deployment/feedback and essential cost reductions [24]. As BEVs emerged and production costs dropped, BEV incentives fell in China, but incentives for FCVs remain in place indefinitely. China tested the market with various financial incentive schemes to off-set high purchase costs of low volume production vehicles, depending on battery or FC size, the extent of electrification on-board and the onboard fuel used (if hybridised). Instruments include tax exemptions, tax credits, priority driving lanes, and waivers on fees (free charging, parking, tolls, etc),



Specific Power
- *The amount of power that the technology can deliver or accept*
- On vehicle performance: acceleration
- On regenerative braking: power limit at which energy can be captured
- On vehicle charging: power limit at which energy can be stored

Lifetime
- *The lifetime of the technology*
- Degradation from manufacture (calendar life)
- Degradation by use (hours life)

Operating Temperature
- *The operating temperature range of the technology*
- Charge / refuel
- Start
- Operate

Specific Energy
- *The amount of energy that the technology can deliver or accept*
- On vehicle performance: range
- On regenerative braking: amount of energy that can be captured
- On vehicle charging: the amount of energy that can be stored

Fig. 3. The key parameters considered when developing a power source or range extender for a NEV (adapted from Jeremy Bowman Integrating Automotive Fuel Cells: http://www.climate-change-solutions.co.uk/past-events/november-17-midlands-showcase-part-2-mhfcn/).

plus government purchasing agreements for public fleets. Exploring the market responses developed a good understanding of the NEV market in China, which is heavily incentive dependent.

4.1. Battery electric cars

The need for NEVs to prevent urban air pollution and as a strategic emerging industry was recognised early in national policy [25], and the focus until now has been BEVs. By 2010, trial incentive programmes for NEV private purchase in selected cities provided payments directly to carmakers, up to specific volume sales, but in 2011, only ~ 8,000 EVs were sold in China despite the subsidy. In 2013, the National Development and Reform Commission (NDRC) and finance, science, and industry ministries confirmed central government subsidies for the purchase of all-electric cars and buses. Between January and August 2014 NEVs (which are mostly EVs) reached > 31,000 units, up 328% from the same period of 2013 [23]. In June 2016, the NDRC and the National Energy Administration released the Energy Technology Revolution Innovation Action Plan (2016–2030) and Roadmap for Action [26]. The market responded resolutely to these policies, creating a successful new model for EVs, and by September 2017 monthly sales of NEVs reached 78,000 units, increasing 79% year on year [23]. Sales of NEVs in China during 2017 will reach 700,000 based on the first nine months of NEV production in 2017 (424,000 units), representing a 40% growth on 2016 figures.

China has hundreds of battery makers and the top 5 hold ~ 70% of the automotive market. Carmakers continue to invest in battery companies or material suppliers as they secure promising/proven core technologies and manufacturing resources [17,24]. For example, Great Wall Motor bought a stake in Pilbara Minerals, with lithium resources in Western Australia. China's CATL has the largest share of the automotive battery market in 2017 (~ 30%). Dongfeng Motor Corp became a shareholder in CATL and continues to acquire battery technologies and mass manufacturing capability. BMW is already a CATL customer and SAIC (China's largest vehicle maker) announced a partnership with CATL in 2017. BYD is China's biggest producer of NEVs and holds almost a fifth of the Chinese automotive battery market, increasing production with the expanding market [24]. These investments in manufacturing required new joint ventures (JVs) e.g. a BMW JV in Shengyang is expected to produce 33,000 high voltage battery packs a year; Daimler has partnered with BAIC Motor.

Unlike the electric bike, BEVs do not provide adequate range because they are heavier and even the best lithium batteries store much less energy per kg than gasoline [4]. They also demand long charging times, making present battery cars inadequate, although needing only half the energy used by combustion cars. Battery packs remain a major cost component of NEVs and drive up retail prices, so financial incentives have been critical to increase sales, production scale-up and real-world technology assessment – their removal will impact the market significantly.

4.2. Fuel cell (FC) cars

The electrification of vehicles opens up the possibility for on-board fuel cells (FCs). FCs convert the chemical energy in fuel directly into electricity, without combustion, leading to high efficiencies with low or even zero emissions. They use fuels containing hydrogen (including infrastructure hydrocarbon fuels such as LPG, ethanol, etc) and produce zero pollution from the tailpipe when operating on pure hydrogen, reducing urban emissions. If hydrogen is produced from natural gas, or if hydrocarbons are used as the fuel, FCVs cut total GHG emissions by ~ 50% compared to today's conventional cars; when hydrogen is produced from renewables or low carbon sources, GHG emissions are reduced > 90% [27]. FCs are scalable across many sectors and applications and hydrogen is increasingly seen as a clean “energy vector”, similar to electricity [28]. FCs already technically proved themselves in niche applications such as the Apollo Missions, and in military theatre where FC system energy densities are not achievable by other technologies e.g. in drones and soldier-portable power. FCVs normally include an on-board battery, which is recharged or used less using a FC. Depending on the state of charge of the battery or the rate of charging, the efficiency of charging can be many times higher than that of combustion HVs, and can be done near silently, even while stationary. FCs and batteries are often considered competitive technologies, but in fact FC systems complement batteries, and the electrification of vehicles allows FCs to be used as range extenders to overcome the key barrier to EV commercialisation – range anxiety. FCs are therefore battery enabling technologies, offering three improvements to pure battery vehicles: (1) range extension to > 300 miles on a single fill, (2) reduced re-charge times – refilling takes a few minutes, (3) lower system weight and (4) extended lifetimes [8].

FCVs effectively use FCs as battery range extenders that work at constant load, and are sized to satisfy the vehicle's average power requirement, rather than peak power required during acceleration. Thus the vehicle achieves the cost and environmental benefits of batteries power, plus the full driving range of the range extender fuel. Proton exchange membrane (PEM) FCs dominate in vehicles to date, but the supply of substantial quantities of hydrogen, the costs of establishing supply infrastructure and the expense of systems have slowed market uptake. FCVs are already being developed and offered on the market as they offer operational advantages and greater economic gains compared to battery manufacture [8]. There were three FCVs available for purchase or lease in 2017: Mirai (Toyota), Tucson Fuel Cell/ix35 Fuel Cell (Hyundai) and Clarity (Honda). Daimler, General Motors, BMW, and others plan to bring FCVs to market soon [29]. Next-generation FCV models planned for 2018 (Hyundai) and 2020 (Toyota), and details on the automakers' activities and plans are presented elsewhere [8]. Even FC technologies previously not considered for vehicles like solid oxide fuel cells (SOFCs) are now proposed by Nissan as innovative vehicle systems [30].

FCs did not yet achieve the costs reductions of mass manufacturing compared to solar PV and batteries, despite low materials costs, because scaled manufacture did not yet begin. Importantly however, while government incentives for BEVs are dropping in China, incentives for FC vehicles are set to continue indefinitely [31]. This long term commitment will no doubt become important as technology development programme times tend to be long; for example, the Toyota Hybrid to Hydrogen vehicle programme was a 25 year plus development cycle. FC and hydrogen (FCH) technology innovation is one of the 15 key tasks listed in the 2016 NDRC Innovation Action Plan and Roadmap [25], which listed target disruptive technologies ripe for industry innovation. The 2020 targets for PEM type FCs are clear in the Roadmap: 50–100 kW power, > 300 Wh/kg by 2020, > 3 kW/L, lifetimes > 5000 h. In the longer term, the ambition is to realize the large-scale application of FC and hydrogen (by 2030) and mass markets for hydrogen energy and FCs (by 2050). The Chinese Society of Automotive Engineers (SAE China) also released a "Technology Roadmap for Energy-Saving and New Energy Vehicles" for China, including the Fuel Cell Vehicle (FCV) Technology Roadmap. In addition, the China National Institute for Standardization (CNIS) and National Standardization Technical Committee on Hydrogen Energy (SAC/TC 309) officially released the 2016 China Bluebook on Hydrogen Energy Industrial Infrastructure. Less clear are technical targets for SOFC and other FC technologies which are still to be defined. Overall, FCH technologies look set to be a focus in China, dwarfing investments by other regions including Europe.

4.3. Fuel cell (FC) buses

There are several hydrogen-fuelled medium and heavy vehicles - including buses - available on the market today [29,30]. Buses have proved a heavily subsidised success in Europe, and are now being deployed in China, with public infrastructure investments supporting centralised refuelling stations. Buses with Ballard FCs were operated in London for > 15 years as part of the CUTE programme [31]. In Europe there are > 60 FC buses in service, with more planned to 2020–21 in 3Emotion, 144 funded under JIVE and 150 under JIVE 2. FC buses replace diesel buses without significant change to operational requirements such as fleet size, route infrastructure, route type and schedule, removing a significant source of fine particle and nitrogen oxides from city centres. The Chinese NEV Program supports FC buses with national and local subsidies, and there are ~30 buses in service in China in 2017, with over 300 buses planned by the end of 2018. Major Chinese bus OEMs are developing FC buses; for example, Yutong, King Long and Yinlong work with system integrators ReFire and UpPowerTech. The world's largest FC bus project is now being implemented in Foshan city, Guangdong province, by a coalition of government and commercial companies [Fig. 4]. The new factory, has a production capacity of 5000 buses per annum, and the bus factory is adjacent to the Ballard FC production line, operated under licence by Guangdong Nation Synergy Hydrogen Technology Co. This makes 15 kW subunits, six of which can be assembled into the 90 kW fuel cell engine to connect to the 39 kWh lithium battery to power the 11 m electric bus.

Fig. 4. 100 buses (8 m) under construction by Feichi, Foshan. The factory is capable of manufacturing 5000 HFC buses per year. Copyright: Prof Kevin Kendall, www.adelan.co.uk.

The FC is an on-board battery charger or range extender, and vehicles have the same electric drivetrain and platform as battery electric buses. Zero-emission FC buses exhibit long range capability (350 km+), fast refilling (< 10 min), centralised refuelling and are now falling in cost due to increasing production. Hydrogen is the zero-emission fuel for FC buses, and can be produced from natural gas, biogas, and electricity (including renewable sources) supporting energy independence. Bus demand stimulates localised hydrogen production, which can stimulate hydrogen market development, delivering low carbon fuel supply and grid stabilising projects such as light and heavy delivery vehicles and rail applications.

4.4. Other NEVs, auxiliary power units (APUs) and range extenders

Although light-duty FCV production is currently limited, demand is expected to increase in urban centres as emissions restrictions increase, and expand as hydrogen fuelling infrastructure grows [32]. Other vehicle applications are forklift trucks, robots, unmanned airborne vehicles (UAVs or drones), autonomous cars, golf cars, mobility vehicles for the disabled, inland and marine boats, autonomous underwater vehicles (AUVs or submarines) and other military vehicles. Incentives are currently available in China for small delivery van and mini-bus NEVs.

NEV sales in China for 2017 are dominated by BEVs, but range anxiety remains a key barrier to wider commercialisation of EVs. Increasing restrictions on emissions from combustion-based vehicles, including hybrids, are leading developers to seek non-combustion based range extenders to extend the driving range. Zero emission range extenders have unique utility where combustion is banned e.g. in conservation areas, tunnels and indoors, and some types of vehicles have been using auxiliary power units (APUs) or range extenders with specific purpose for years. Intelligent Energy demonstrated one of the first PEM FC range extender which was a roof- mounted 4 kW FC system and hydrogen fuel tank that had no impact on vehicle load space [8].

Adding and testing range extender technologies becomes easier once vehicles are pure electric. Decoupling the power supplied by the range extender from the (battery) power demanded by the driver opens multiple range extender technology options. The challenge is to design the right hybridised system to suit the various NEV models, which vary especially in weight [4]. The California Air Resources Board (CARB) have very specific definition of range-extended battery-electric vehicle (BEVx) [33], but range extenders are yet to be well-defined for specific vehicle models and are a rapidly expanding space in commercial R&D. Some estimates predict > 11 million range extenders are needed by 2028, to satisfy the lower power requirements predicted with fast charging and energy harvesting innovations [34]. Supercapacitors, micro turbines, Wankel engines, rotary combustion engines or free piston engines and flywheels are also being tested as range extenders.

5. NEVs in China: fuel cell research priorities

5.1. System design and integration

System engineering of FC technologies into marketable vehicles is the next key step in the NEV programme. However, the challenge to date has been determining which technologies have promise or are the most promising in the Chinese market. Knowledge based engineering (KBE) can be used to evaluate and optimise a technology once basic research questions have been answered. However, evaluation and standardised comparison of these technologies requires a scientific and national objectivity that remains elusive. This is particularly difficult as experts in specific FCs cannot necessarily compare their FC against other technologies, scientifically or objectively. The complexity and maturity of the different technologies varies greatly across the technology readiness level (TRL) spectrum, and prospective costs are also difficult to predict since manufacturing readiness levels (MRL) are even lower. A publicly funded systematic global review by a non-partisan grouping of expert international scientists may help to identify a list of credible technologies of proven longevity. Current programmes of system integration of FCs are not exhaustive, often driven by non-scientific objectives and do not cover a standardised set of deployment conditions to demonstrate technology strengths and weaknesses. A global programme would require massive public investment, but the benefit could be that much of the data will be accessible and shared. Alternatively, private companies will continue to deploy technologies under more secretive testing regimes and the data (both positive and negative) will remain within commercial entities in the private sector, for value only to be demonstrated in the market place following product release. Private-public investment delivered PV and battery technologies to the market in China; China may apply a similar strategy to deliver FC technologies.

5.2. Reducing costs and manufacturing

The major barrier to NEV deployment in China is still cost, and cost reductions are required across the innovation spectrum. Scale up of automotive battery manufacture has now become a major focus of R&D in China to reduce battery costs for the NEV market, with artificial intelligence and automation a strong focus. As PEM FCs gained commercial traction, work to further reduce platinum metal costs accelerated, mostly through materials research (platinum is the most expensive material used in today's NEV FCs), but also through lean manufacturing. Achieving economies of scale through scaling up FC manufacturing is a proven pathway to reduce clean energy costs, as demonstrated by PV in China. China also achieved this with batteries, so China is expected to eventually demonstrate similar cost reductions for FCs, mostly through scaling up production. European projects such as DIGIMAN (http://digiman.eu/) seek to develop the manufacturing approach to PEM components to facilitate high volume automated manufacture and inspection capability throughout the supply chain. Raising the manufacturing level of PEM FCs is being achieved through design for assembly, automated processes for assembly and inspection, and automated materials acceptance standards. Developing comparable automation solutions for SOFCs have not yet been funded by FCH JU2, but the potential for even greater advance in SOFC manufacture has been demonstrated on a Marie Curie funded academia-industry project led by SOFC maker Adelan UK (www.birmingham.ac.uk/newgensofc/). The material costs proved not to be a barrier to market products integrating this technology, but scaling to volume manufacture proved critical to achieving price competitiveness against competitive technologies. The Ballard plant in Foshan, China has already been built for PEM; again an equivalent Chinese plant for SOFC stack manufacture is still to be agreed.

5.3. Performance

More than 200 PEM FCVs driving over 6 million miles were validated in real world conditions by the US Department of Energy (US DOE; [8]). The Recovery Act funded 1600 further PEM FCs that enabled 18,000 forklift and backup power units, demonstrating the use of FCs as BEV enabling technology to maximise battery performance. Since battery lifetimes can be extended using FCs, batteries may find second life applications again enabled by FCs, e.g. as stationary power storage.

In 2015, commercial FC shipments rose sharply worldwide, demonstrating growing traction in the marketplace, and many FCs were used as range extenders for batteries. Direct comparisons of FCs with batteries will also be critical to evaluating which technology delivers the required performance [24]. Improving NEV range using FC range extenders (either PEM or SOFC), and meeting other NEV product capability expectations such as powering on-board electrical demand using FC APUs could widen market acceptance of FCs on vehicles. Due to growing interest in intelligent vehicles, extending the range of autonomous vehicles using FC range extenders could be the ideal opportunity to demonstrate FCs for range extenders and APUs. UK companies are evaluating FC range extenders for autonomous vehicles as a potential solution to lengthy charging periods.

5.4. Materials and nanomaterials

Materials research is a critical part of accelerating FC technologies to market, although arguably in China there is more focus on system development through deployment. Growing application areas like range extenders still offer test-beds and proving grounds for new materials. Materials research and innovation can support transition towards a global, long-term solution to atmospheric emissions. However, the number of scientists working in FC materials for example is still very low, with NEV communities dispersed across the world with different regional strengths, technologies and challenges. Materials R&D for FCs is a global activity strongest in developed knowledge economies, and these well-established groups could be harnessed by the NEV industry in China to accelerate delivery of new materials for FCs. For example, materials R&D enabled significant improvements in PEM technology, cutting platinum use five-fold, and resulting in a 50% reduction in costs since 2007 while quadrupling durability [8]. This led China to be the first to mass manufacture PEM technologies.

The NEV field has been traditionally held back by materials deficiencies in performance, lifetimes and costs. One key limitation for FC development is the number of people working in the FC field, continuity of R&D groups, succession planning, cooperation failure between academic and commercial sectors, a lack of diversity and barriers to international research. International programmes such as the EU-funded FCH JU have shown both the benefits and limitations of coordinated actions, and total expenditure remains low compared to nuclear or fossil fuel R&D. Some groups (for example women) are almost absent from agenda setting activities in these R&D programmes in Europe, highlighting a lack of social inclusion in the European STEM community.

Increased R&D funding into FC materials for NEV technologies is required to accelerate progress in this area. For example, the materials complexity issue for SOFCs is multi-factorial, requiring a complex skills base to address multidisciplinary problems:

- Conductivity
- Mechanical strength
- Operation at temperatures > 300 °C
- Composite behaviour
- Triple phase boundaries
- Catalysis
- Manufacturing processing
- Cost reductions

R&D initiatives can promote global collaboration to connect and network the best scientists and engineers internationally, creating new models of international cooperation for clean energy. "Mission Innovation" (MI) is a goal-oriented initiative committing 20 countries (including the UK and China) to double public sector budgets for targeted clean energy R&D. MI prioritises the scientific challenges of climate change, including advanced materials discovery and development challenges, but the benefit is yet to be demonstrated. The Breakthrough Energy Coalition, a group of private investors aligned with MI, promised investment of up to $20 billion into the most promising new clean energy technologies. MI countries identified seven key Innovation Challenges aimed at accelerating clean energy research, development and demonstration, including "#6: Clean Energy Materials". A workshop for Innovation Challenge #6 was held in Mexico City in September 2017, led by Mexico with the US [9], where inverse design of materials by artificial intelligence was proposed to accelerate materials discovery. In parallel, a WEF Public-Private Partnership Workshop on Clean Energy discussed policies to engage private enterprises – especially patient capital. Again, talented groups can remain excluded from these discussions (e.g. women), indicating that significant talent remains untapped. A more radical approach could allocate resources to those absent from prior programmes e.g. invest in a previously poorly resourced group such as women to lead research agendas. For new clean energy materials or technologies, a well-to-wheel approach must be taken going forwards, and life cycle analysis (LCA) comparisons with common or potential battery chemistries will be critical to strategic alignment with environmental goals [24].

5.5. *Strategic intervention policies: NEV infrastructure*

While FCs are not yet fully commercial, much was learned from the commercialisation of batteries and PV, where China played a key role as lead manufacturer and deployer [10]. The earlier commercialisation of PV technologies via volume production highlighted the need for more cost effective materials, materials processing and manufacturing, and demonstrated the time required for market development once a minimum viable product is developed [10]. The markets took decades to respond, following strategic policy implementation in Germany and California in the late nineties, and this may be ineffective for climate protection where substantial progress is required within a decade – radical interventions are therefore appropriate. The market itself is innovating novel business models such as new vehicle ownership models, and potentially less car ownership in response to financial incentives.

Demonstration projects have proven crucial in developing NEV markets, systems and supply chains. Early commercial deployments led to technology maturation, and an early market focus allowed market testing. Nationally consistent strategic policies and market frameworks which integrate energy and transport systems better, worked best [7]. Hydrogen NEV trials are now examining the costs of refuelling infrastructure to match the hundreds of thousands of infrastructure fuel stations in Europe and the US – across these regions there will be ~ 100 hydrogen stations by the end of 2017. Even assuming hydrogen infrastructure will establish over time, SOFCs operating on readily available infrastructure fuels are being considered for vehicle range extenders, if only to gradually transition to a hydrogen economy which will take decades to build up.

EV deployment demonstrated that recharging protocols by the local grid varied across regional projects and industrial sectors. National infrastructure standards for all regions and developing NEV models are required; international coordination is required to develop uniform standards uniting requirements in different areas, for locally produced and imported NEVs. R&D is increasingly focused on low-cost hydrogen produced from fully carbon-free pathways, and storage solutions from stationary to mobile applications (e.g. heavy metal hydrides and lightweight tanks). Innovation in hydrogen production, delivery, and storage will drive wider deployment of FC technology, and electricity generation and storage at grid and community scale is moving from centralized to distributed systems, where excess renewable electricity is harnessed for hydrogen production [10]. Hydrogen is then used as an integrator – an "energy vector", enhancing energy security and enabling transition to a carbon free economy, with additional air quality benefits.

6. Conclusions

Air pollution kills an estimated 7–10 million people a year globally, more than the victims of all the terrorists, wars and homicides combined. This remains a significant reason for FC NEV promotion across the world and is also stimulating FC development for stationary power. Decarbonization of energy is also a major stimulus of NEV policies in China, to reduce GHG emissions fast enough to prevent the worst impacts of climate change, particularly amongst the world's poorest and most vulnerable. Addressing the energy trilemma will bring many benefits for China, and Chinese leadership in this area will have global impacts on markets and manufacturing capacity. China is unique in its multi-objective optimization of the NEV market, and the scale of testing new markets. Strategic initiatives in China are coordinated and consistent in the largest world market, where the market is tested rigorously, through strongly subsidised policies. Due to the different national drivers, China acts as a complementary testbed to contrast with the rest of Asia, the US, UK and Europe.

The NEV policy aligns with a growing movement to electrify energy systems, and which is also still open to new technical options. Global equality of access to clean electricity worldwide remains a significant socio-economic challenge. Increasingly distributed renewable power is leading to remote electrification, and hydrogen is one option for energy storage and delivering a carbon free transportation system. However, there is currently an uncertain energy landscape and the adoption of hydrogen requires considerable untested changes in fuel infrastructures for developed countries. PEM FCs operating on hydrogen or SOFCs operating on infrastructure hydrocarbon or hydrogen fuels offer a number of air quality advantages over existing propulsion technologies. FCs are key to future powertrain development in NEVs at the very least as range extenders and auxiliary power units (APUs) for on-board electronics. It is critical that any policy to clean city centre air is tied to clean production processes during product manufacture, and China is likely to play a major role in manufacturing FCs as it has done in the PV and battery industries. Based in historical data from these industries, international R&D programmes to support FC NEVs must take radical steps quickly if they are to contribute to delivering technologies to market as a clean air intervention policy. The key challenges lie in scaling up FC technologies and commercialising them into real markets.

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