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To cite this article: Mario Pagliaro and Francesco Meneguzzo 2019 *J. Phys. Energy* **1** 011001

IOP Publishing J. Phys.: Energy 1 (2019) 011001 https://doi.org/10.1088/2515-7655/aacd9f

JPhys Energy

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OPEN ACCESS

PUBLISHED
20 November 2018

PERSPECTIVE

The driving power of the electron

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Keywords: electric vehicles, solar hydrogen, energy transition, renewable energy, Li-ion battery

Abstract

Almost two centuries after Carnot's 1824 *Réflexions sur la puissance motrice du feu* (Paris: Bachelier Libraire), electricity stored in Li-ion batteries or made available by hydrogen fuel cells onboard, is becoming the energy form powering the mobility of vehicles, including: cars, buses, trucks, boats and ships. The conflicting dynamics of global wealth, energy and population requires the replacement of fossil fuels with truly renewable energy sources (sun, water and wind). This also implies the replacement of the ubiquitous internal combustion engine with the much more efficient electric motor powered by renewable electricity. Will the availability of lithium or cobalt intrinsically limit lithium battery manufacturing rapidly driving up battery production costs? Can we expect hydrogen fuel cell electric vehicles to become widely adopted as it is currently taking place with battery electric vehicles? Referring to recent research and industrial achievements, this study offers an answer to these and related questions.

1. Introduction

The year 2017 was a turning point for electric cars, namely automobiles with an electric motor powered by rechargeable lithium batteries or by hydrogen fuel cells. For the first time, the number of electric cars sold across the world surpassed the 1 million threshold (1200020), growing at 57% rate over the previous year [1]. China alone in 2017 saw the registration of 579 000 new battery electric vehicles (BEVs), followed by the US with 195 140 units. Norway, with five million inhabitants only, had a yearly increase of 62 320 electric passenger cars [2] thanks to generous incentives financed by a small fraction of the huge financial surplus accumulated by the country through its oil company selling North Sea's oil and natural gas for decades. Thanks to a well-planned and executed electric vehicle (EV) policy which includes the deployment of the charging infrastructure, Norway is the world's first country where the market share of EVs went from 3%–21% in just five years [2].

Similarly, in 2017 the record number of 3000 units of the first mass-produced hydrogen fuel cell electric car (Toyota Mirai) were sold across the world with a cumulative 6548 units produced in Japan since December 2014 through the first week of March 2018 [3].

Users are generally satisfied with their new electric vehicles [4], which are more pleasant to drive due to lack of noise, vibration and polluting emissions, not to mention the driving precision due to the electric motor, making available its maximum torque at zero speed [5]. In brief, almost two centuries after 1824 Carnot's *Réflexions sur la puissance motrice du feu* [6], namely the scientific milestone in which Carnot showed that the maximum efficiency of a mechanical engine exchanging heat with two sources only depends on the temperatures of these sources [7], electricity is becoming the power source of EVs manufactured on an industrial scale. So far, most EV applications of *la puissance motrice de l'électron* include electric cars, vans and buses, even though trucks and ships will shortly have electric motors powered by hydrogen fuel cells and, for heavy-duty vehicles travelling short distances, also by Li-ion batteries.

For example, since 2015, the world's first fully electric ship carries 34 times a day a maximum of 360 passenger and 120 vehicles for the brief distance (5.6 km) between Lavik and Oppedal in Norway's Sognefjord at an average speed of 10 knots. The results of the first two years of navigation are impressive: 80% reduction in operational costs, and 1 million L of diesel fuel saved [8].

Table 1. Global EV registrations in 2017, by country and by manufacturer[a].

Country	Registrations	Manufacturer	Registrations
China	579 000	BYD	99 870
USA	195 140	BAIC	96 670
Norway	62 320	Tesla	86 770
Japan	56 000	BMW	67 940
Germany	54 490	Volkswagen	52 520
UK	47 260	Toyota	49 860
France	41 720	Nissan	45 000
Sweden	20 310	Mitsubishi	21 920
Canada	18 390	Ford	21 500
Spain	8330	General Motors	20 850
Switzerland	8020		
Rest of World	100 000		

[a] Source: Centre for Solar Energy and Hydrogen Research Baden-Württemberg, 2018.

All power is retrieved by two Li-ion battery packs, each with a capacity of 520 kWh [9]. The electricity supplied to the batteries, furthermore, is entirely renewable as it originates from a near hydroelectric plant.

Driven by the conflicting dynamics of global wealth, energy and population [10], the internal combustion engine running on oil-derived fuels needs to be replaced by the versatile and much more efficient electric motor. The process has been overly slow mostly due to the obsolescence of conventional batteries and by the high cost of first-generation industrial fuel cells.

Industrially significant change occurred when large scale manufacturing of lithium batteries and EVs started in China in the early 2010s. If, as lately emphasized by Tillmetz [11], the growth rate of EVs remains that observed between 2016 and 2017, the number of EVs registered annually by year 2025 will exceed 25 million.

Will the availability of lithium or cobalt minerals intrinsically limit the expansion of lithium battery and electric vehicle manufacturing rapidly driving up costs? Can we expect hydrogen fuel cell electric vehicles (FCEVs) to become widely adopted as it is currently taking place with BEVs?

Referring to recent research and industrial achievements, this study offers an answer to these and related questions. The resulting unified overview produced at the dawn of the global transition to EVs in the context of the fully unfolding transition to renewable energy and distributed generation, will be useful to: policy makers, researchers, students, entrepreneurs, managers and innovation practitioners, including management consultants of the clean energy industry.

2. The enabling technologies

The enabling technologies powering EVs are the Li-ion battery and the hydrogen fuel cell. In the following we briefly review recent achievements and provide a critical outlook.

2.1. The Li-ion battery

Numerous excellent books [12] and reviews [13] detail the historical background, theory, design, production and use of Li-ion batteries, including recent volumes dedicated to the important issue of Li recovery and recycling [14]. Since over a decade, the lithium battery industry is growing at fast rate (a 20% compound annual growth rate is expected from 2016–2022) [15]. China is leading the ranks in terms of battery and BEV manufacturing (table 1).

Rapid and continuous improvements concern better cathode, electrolyte, separator and manufacturing process [16]. The practical outcome is that Li-ion battery packs of ever higher capacity are replacing the first BEV battery packs with their typical 20 kWh capacity. For instance, a successful EV manufactured in Europe (Renault ZOE) is now equipped with a 41 kWh battery pack with a driving range of 400 kilometers, which almost doubles that of the previous version with a 22 kWh battery pack.

In general, up to 2017 the battery was claimed to represent a third of the cost of a BEV, with the cathode being the most valued component of the battery [17].

Following the first main Li-ion batteries on the market in the 2005–2014 decade based on lithium cobalt oxide ($LiCoO_2$, LCO) cathode, new lithium nickel manganese cobalt oxide (NMC, $LiNi_xMn_yCo_zO_2$) and lithium manganese oxide ($LiMn_2O_4$, LMO) layered cathodes were commercialized. Cobalt, however, is toxic and its supply mostly originate from one country only (Congo, with nearly 60 percent of the world's output).

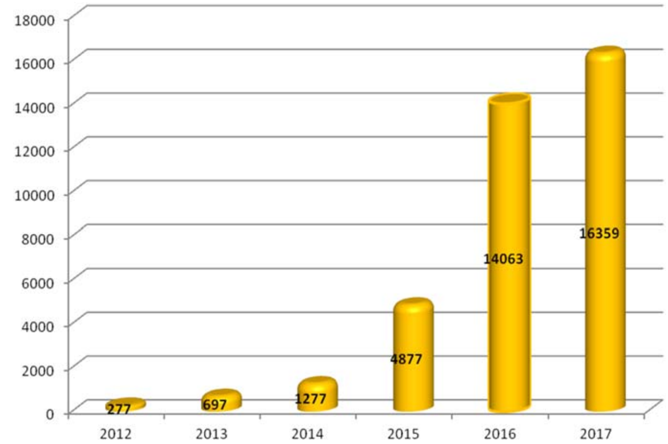

Figure 1. Number of electric buses in Shenzhen, China, 2012–2017. (Source: Shenzhen Urban Transport Planning & Deisgn Institute, 2018).

Indeed, driven by strong demand the price of cobalt has more than doubled between 2016–2017, continuing to rise rapidly in the early part of 2018 (+24% only in the first three months of the year) [18].

On the other hand, lithium iron phosphate (LFP, $LiFePO_4$) in olivine crystal structure is the intercalation material with which are fabricated, for example, the cathodes in the batteries of all 16 359 electric buses comprising since 2017 the entire fleet of buses in the city of Shenzhen, China (figure 1).

Cobalt-free LFP batteries have a higher overall power density than other Li-ion batteries, and a lower energy density. To improve the poor electronic conductivity of $LiFePO_4$ the cathode is coated with a heat-resistant microporous carbon layer inhibiting the exfoliation of $LiFePO_4$ and limiting self-discharge. The anode used in these batteries is generally comprised of graphite, whereas ethylene carbonate dissolving lithium fluoride is the electrolyte.

Along with superior thermal and chemical stability (no overheating and consequent risk of explosion), LFP batteries deliver reliable and consistent performance throughout their service life. Furthermore, $LiFePO_4$ batteries have a very constant discharge voltage, with voltage remaining close to 3.2 V during discharge until the cell is exhausted. This allows the cell to deliver virtually full power until it is discharged.

Actually, Li-ion batteries of LFP chemistry are so stable towards discharge that recently, scholars in the UK were able to propose a protocol that removes the hazard enabling safer transport of Li-ion batteries during long-haul transportation by simply removing 99.1% of the battery's energy [19]. Indeed LFP cells stored at such low state of charge values did not exhibit degradation or any irreversible capacity fade.

Accordingly, in 2016 Li-ion battery with LFP cathode was the main commercial lithium battery technology (with 36% of the market), followed by NMC which offers higher energy density. The latter density is influenced by the crystallographic density of the cathode structures, which decreases in the order: layered oxide $>$ spinel $>$ olivine [20]. Therefore, a scholarly team recently concluded that 'LFP is expected to be replaced in this application (i.e. automotive) by layered cathodes to satisfy higher energy density requirements' [21].

However, the use of phosphate avoids cobalt's cost and environmental concerns through improper disposal, as well as the potential for the thermal runaway characteristic of cobalt-containing cells. Avoidance of cobalt, in addition, translates into reduced supply risk when compared to all the other commercial Li-ion battery technologies [22].

Accordingly, commenting on the cathode technology in Li-ion batteries (table 2), financial analysts based in Canada were not long ago reporting that: '…the idea that LFP will be completely replaced is questionable and we believe that while LFP's market share will slowly drop, the battery will still be at a ~24% share in 2025. Part of LFP's longevity on the market will be in the electric bus market, as they are large enough to house a very large battery… to get the necessary range' [23].

The production of cobalt-containig cells will certainly continue to grow as has happened in the last two years. Yet, we argue, LFP batteries might remain the dominant Li-ion technology for several years to come, with LFP projected to grow at compound annual growth rate of 22.4% from 2017–2025 [24].

A simple and scalable approach to LFP batteries with greater energy storage capacity and much quicker charging times, indeed, was demonstrated by Li and co-workers in Taiwan as early as 2013 [25].

The team incorporated 2 wt% graphene obtained via electrochemical exfoliation of graphite on the surface of commercial carbon-coated lithium iron phosphate (cLFP). The reversible reduction-oxidation reaction

Table 2. Market share and chatode composition of main commercial Li-ion batteries in 2016. (Source: BMO Capital Markets, 2018).

Active material	Market share (%)
LFP	36
NMC	26
LCO	21
NCA	9
LMO	8

Table 3. Compressed and liquid hydrogen properties[a].

Property	Liquid	Gas, 300 bar
Density	70.85 g L^{-1}	20.77 g L^{-1}
Volumetric energy density	2.36 kWh L^{-1}	0.69 kWh L^{-1}
Mass energy density	33.3 kWh kg^{-1}	33.3 kWh kg^{-1}

[a] Reproduced from [29], with kind permission.

between the Li^+ ions in the electrolyte and the graphene flakes translated into 208 mAh g^{-1} specific capacity, namely much higher than the specific capacity of carbon-coated lithium iron phosphate (120–160 mAh g^{-1}) cathode commercially available in 2013.

Along with a 37.2% increase in energy density, the highly conductive graphene flakes also assist the electron migration on the surface of cLFP during the charge/discharge processes enabling the composite electrode to withstand high discharging rates.

Now that graphene of high quality (flake high purity and large dimension) is produced in industry at affordable cost thanks to mild chemical graphite exfoliation methods [26], its use to manufacture enhanced LFP cathodes for Li-ion batteries is likely to emerge as one of its main forthcoming industrial applications [27].

Similarly, in late 2017 Daimler invested $60 millions in Israeli company StoreDot whose 'flash battery' technology allows to quickly recharge EV lithium-ion batteries thanks to the organically modified electrodes [28]. A metal oxide cathode (such as the LFP cathode) modified with peptide polymers allows Li ions to flow from the anode to the cathode at fast speed, basically charging like a supercapacitor and discharging like a battery.

2.2. The hydrogen fuel cell

The other clean technology that will find widespread utilization to power the electric motors of new generation vehicles is the H_2 fuel cell. Thanks to the high energy density of compressed and liquid hydrogen [29] (table 3) and good energy efficiency of today's fuel cells, compressed hydrogen and fuel cells give unprecedented high range and very short refuelling time. For example, a state of the art FCEV is refuelled with hydrogen compressed at 350 bar (or even at 700 bar in today's refuelling stations) in less than 5 min obtaining a 500–600 km autonomy (Hyundai's Nexo delivers a full-tank driving distance of 609 km, while Toyota's Mirai has a 500 km range).

When compared to Li-ion batteries, hydrogen fuel cells are better suited to power heavy-duty vehicles, including trucks and ships. For instance, the large battery electric ferry commuting between the 5.6 km distant ports in Norway mentioned above requires charging with approximately 1200 kWh every time the ferry is at port using a 12 MW charger requiring cooling, while the battery racks are embedded with a liquid cooling system [30].

After decades of moderate growth and little or no profits, 2017 was the first year in which numerous fuel cell companies reported significant revenue increases and profits (table 4).

Growth has been due to increasing demand from all main fuel cell applications including forklifts powered by H_2 used by large e-commerce and hypermarket companies in their high-throughput distribution centers, especially in the US where by mid 2017 already ~3% of the more than 600 000 forklifts used in warehouses already run on hydrogen [31], when a forklift powered by a hydrogen fuel-cell pack costed $58 000 about twice as much as one with powered by lead-acid battery.

An hydrogen-powered forklift is charged in minutes instead of hours, eliminates the labor cost of charging batteries and frees valued warehouse space thereby keeping goods flowing in organizations where reducing processing time is crucial to ensure customer satisfaction and maximize revenues.

Figure 2. Coradia iLint hydrogen-powered train arriving at Frankfurt-Höchst station on 13 April 2018. (Image courtesy of Matthias Oestreich.)

Table 4. Revenues in 2017 for three representative PEM fuel cell manufacturers.

Company	Country	Year on year revenue increase	2017 Revenue (in million USD)
Hydrogenics	Canada	+66%	48.1
Plug Power	USA	+55%	132.9
Ballard Power Systems	Canada	+42%	121.3

Remarkably, in March 2017 a train manufacturing company successfully performed the first test (at 80 km h^{-1} maximum speed) of the world's first hydrogen fuel cell passenger train (Coradia iLint) on a test track in Lower Saxony (Germany) [32]. The train, whose production model can cover up to 1000 km with one hydrogen tank, carrying 300 passengers and reaching a maximum speed of up to 140 km h^{-1}, made a promotional run from Wiesbaden to Frankfurt-Höchst in April 2018 (figure 2).

All tests were largely successful and the first contract to supply the Local Transport Authority of Lower Saxony with 14 H_2-powered trains that will convey passengers from December 2021 was signed shortly afterwards; [33] followed by a tender notice published in the Official Journal of the European Union on 20 April 2018 to supply Frankfurt Rhine-Main Vehicle Management with a fleet of hydrogen fuel cell trains for regional services on non-electrified lines.

The 25-year availability-based contract calls for the supply and maintenance of the new trains along with refuelling infrastructure. In each case, the electric trains running on hydrogen fuel cells will replace diesel-powered trains. The Coradia iLint manufacturing company will build 60 trains within 2022, including some for UK railways, and was forced to refuse new orders from Austria.

It is also remarkable, from a practical viewpoint, that in late 2017 the first platinum-free fuel cell (a 30 W fuel cell stack dubbed FCgen-1040) was commercialized by a leading proton exchange membrane (PEM) fuel cell manufacturer based in Canada [34]. Platinum in fuel cells is the electrocatalyst needed to promote the oxygen reduction reaction. We also remind that PEM fuel cells, operating below 100 °C, are the leading fuel cell technology. The new PEM fuel cell relies on a nanostructured carbon catalyst introduced by a company in Japan and further developed with scientists based at the fuel cell manufacturer [35]. In closer detail, the catalyst is comprised of carbon alloyed with low cost Zn, added as $ZnCl_2$ dissolved in dimethylformamide in the early phase of the catalyst synthesis.

Sufficient for backup power and portable power applications, the power achieved under an air/H_2 mixture was the highest (0.570 W cm^{-2}) to date for a practically relevant (50 cm^2) membrane electrode assembly [35].

Table 5. Number of plug-in positions for EV charging in top ten European countries and in the UK by the end of 2017[a].

Rank	Country	Plug-in positions
1	Norway	186 300
2	France	146 799
3	UK	142 560
4	Germany	126 205
5	Netherlands	98 625
6	Sweden	52 063
7	Belgium	35 300
8	Switzerland	24 174
9	Spain	19 896
10	Austria	18 530

[a] Source: European Alternative Fuels Observatory, 2018.

3. The enabling infrastructure

The infrastructure enabling the transition to EVs will be comprised of plug-in EV charging points and H_2 refuelling stations where hydrogen is obtained from water via on-site electrolysis. Both will use electricity available via the grid, or generated on-site with PV modules or wind turbines.

3.1. EV charging infrastructure

The deployment of EV charging points is rapidly taking place across the world (table 5). Typically, an alternating current (AC) charging station supplies current to the vehicle charger, whereas a direct current (DC) charging station supplies current directly to the car's battery pack.

China (where the GB/T charging system is used) has the world's largest EV charging network with the number of charging points having reached 450 000 in 2017, including around 210 000 charging points publicly accessible [36]. It is also relevant to note herein that these chargers in 2017 were used for 15% of the time [36], showing how the charging infrastructure in China in 2017 was already capable to serve several million EVs.

For comparison, by the same date the US hosted slightly more than 47 000 charging points (and slightly more than 16 000 public stations) [37], whereas Japan (where the CHAdeMO charging system is the standard) had 19 194 charging stations (7200 of which charging at >22 kW) [38].

In Europe by early 2018 Norway, with only 5 million inhabitants, was leading with over 186 000 of plug-in positions, when Germany, with a population exceeding 80 million, did not reach 130 000 positions [39].

The world's largest country, Russia, by the end of 2017 hosted less than 1000 charging points, mostly located in its main western cities. However, the number of EVs registered in Russia in 2017 grew by 92.5% to 1771 units as drivers may typically charge 20 kWh spending 40 rubles ($0.65) if charging at night, or 60 rubles ($1.04) during the day [40]. In general, the country's charging infrastructure is rapidly expanding with the State-owned power company Rosseti currently building a network of EV charging stations for EVs that will link Kaliningrad on the Baltics to main Siberian cities to include all major Russian cities and highways across the territory up to Vladivostok. To promote adoption of EVs, in some cities the charging service is even offered free of charge [41].

In India, the world's second most populous country, the city of Nagpur in 2017 became one of the first to host an EV charging station, after having introduced in May 2017 a fleet of 200 EVs for public transport, including taxis, buses, e-rickshaw and cars [42].

On 26 April 2018, India's Government had already completed the second EV tender notice for delivering another set of 10 000 EVs to be used by Government departments and agencies. The successful bidder in the first tender for 10 000 electric cars finalised in September 2017 was an Indian electric car maker (Tata Motors) [43].

On 7 March 2018, India's Government announced a national electric mobility program targeting 30% of cars on the road electric by 2030, abolishing the need of licenses to open EV charging stations.

3.2. Hydrogen refuelling stations

The widespread uptake of hydrogen fuel cell EVs requires the construction of hydrogen refuelling stations to supply with compressed H_2 fuel cell cars, buses, trucks and, in the near future, also trains, boats and ships.

Figure 3. An aerial picture of the world's largest hydrogen refuelling stations production plant, operated by NEL Hydrogen, in Denmark's Herning. Imagery ©2018 Aerodata International Surveys, DigitalGlobe, Scankort, Map data ©2018 Google.

It may not be surprising, therefore, that a progress similar to that in fuel cell technology recently concerned water electrolysis technology [44]. In today's hydrogen refuelling stations compressed H_2 is produced by water electrolysis using state of the art electrolysers and by compressions via newly developed compressors.

A few specialized companies operating worldwide already offer turnkey hydrogen refuelling stations mostly based on alkaline water electrolysis with typical capacities ranging from 100–200 kg of hydrogen per day, and hydrogen dispensed at 350 bar or even at 700 bar.

To put progress in perspective, it is enough to consider that one of the leading H_2 station manufacturers operates a factory (figure 3) with a capacity up to 300 stations (with several dispensers) per year in Denmark. A single dispenser has a fuelling capacity of up to 100 cars or 50 buses per day [45].

Hydrogen is sold by the kilogram. By March 2017, a company operating five hydrogen refuelling stations in California was the first to break the $10/kg barrier, with 1 kg of hydrogen sold to FCEV owners at $9.99 per kilogram [46]. For comparison, by mid 2017 the leading manufacturer of hydrogen refuelling stations in the UK signed a contract to supply Honda (maker of the Clarity FC electric car) with hydrogen at £10/kg throughout its network comprised of ten H_2 stations [47]. Honda's Clarity is commercialized at a monthly fee ($369 a month, in California and $2800 due at signing) including free hydrogen over the first three years.

According to the California's Energy Commission, the cost per station of producing 1 kilogram of hydrogen fuel has fallen from $8.689 to $6.409 in only two years, with a per-station cost around $1.5 million [48]. In Japan, currently the country with the largest number of hydrogen refuelling stations, as of March 2018 the cost of building a station was reported between 400–500 million yen ($3.8–$4.7 million), namely four–five times higher than a gasoline station [49].

After years of slow growth in which existing H_2 stations were even abandoned (i.e. in Italy), the hydrogen refuelling infrastructure is finally being deployed at fast pace, even though rate will have to increase beyond the 25% annual growth rate recorded in 2017, when the number of hydrogen stations worldwide reached the 328 threshold, with 64 new stations opened throughout the year [50].

Only Germany in 2017 added 24 stations. India and United Arab Emirates saw the opening of the first H_2 stations whereas Russia continued to host none.

China opened its first hydrogen refuelling station in 2007. In early 2018, the country's Government reassured that fuel cells were an important part of the development of new energy vehicles, with plans to build a hydrogen infrastructure to support up to 1 million FCEVs by 2030 [51]. In the early months of 2018, three new hydrogen fuel cell buses entered service and the first hydrogen refuelling station was opened to the public in southwest Sichuan Province [52].

In South Korea, the Government and Hyundai recently partnered with State-owned Korea Gas Corporation and other companies establishing a special purpose company that will install eight new H_2 filling stations in the country's main highways and another ten in Seoul and other large cities of the peninsula [53].

4. Industrial perspectives

4.1. The lithium battery industry

'I do not understand why our firms have hesitated for so long to catch up with EVs', publicly commented Germany's economy minister in April 2018, adding that 'the German automotive industry must invest heavily in electric car technology and develop battery production facilities in Europe to keep up with global competitors. Otherwise we'll have to accept that a large part of the added value will be produced in Asia or the United States, instead of here with us' [54].

Out of 3.2 million electric cars circulating at the end of 2017, indeed, some 1.2 million were on the roads of China, and about 99% of the 385 000 electric buses on roads across the world in 2017 were in China, already accounting for 17 percent of the country's entire fleet [55]. The trend recorded in early 2018 is such that every five weeks, Chinese cities add 9500 zero-emissions electric buses. For comparison, in 2017 across the whole of the UK, there were 344 electric and plug-in hybrid buses [55].

Exactly as it happened with photovoltaic cells and modules, well-planned public subsidies to BEVs have been key to incentivise demand, quality in manufacturing and cost reduction. For example in China, subsidies to the buyers of electric passenger cars changed in early 2018, cutting the incentive for cars with a driving range of less than 300 kilometers, and raising it (from 44 000–50 000 yuan) for electric cars that have a range of 400 kilometers and beyond on a single charge; with only EVs having battery energy density above 105 Wh kg^{-1} now being eligible for the subsidies (the previous threshold was 90 Wh kg^{-1}) [56].

By the end of 2017, when the overall lithium ion cell demand was around 100 GWh, market analysts tracked 26 battery cell plants due to expand capacity or start operations to reach out a combined planned capacity of 344.5 GWh by 2021 [57].

Aiming to secure supply and reduce dependence on the three main suppliers of lithium carbonate, which in 2016 owned around 90% of the world's lithium market [58], several Chinese companies which so far relied on lithium carbonate imported from Chile, Argentine and Australia [59], recently bought stakes in lithium mining projects abroad.

Indeed, as shown by Narins [60], the recent increase in $>$99.5%, Li_2CO_3 price (2017 average price around $13 900/t *versus* $7400/t in 2016) [61] has been due more to a consumption-production imbalance rather than to quantity.

In other words, access to lithium is limited more by logistical issues (cost-effective access) and quality than actual availability. In Narins' words, 'that the world's largest known lithium reserves exist in a country (Bolivia) that is not among the world's largest lithium producers is a paradox that further adds to the contradictions surrounding global lithium availability' [60].

In India, discussions were ongoing by the end of 2017 on where to locate the first 25 GWh Li-ion battery factory (a $3.5 billion investment) and at least four major industrial groups were in the process to start new large lithium battery factories [62]. It is instructive, and somehow revealing on the true cost of Li-ion battery and BEV manufacturing, to notice how the first competitive bidding to supply the Government with 10 000 EVs won on September 2017 by Tata Motors included supply of an electric car equipped with a 85 kW electric motor and range of around 100 km for INR 1120000 ($ 16 768) [43].

In Russia, since 2011, state-owned Liotech operates a large plant manufacturing lithium batteries with $LiFePO_4$ cathodes of different capacities in Novosirbisk. The company was a joint venture between Rusnano and one of China's leading battery manufacturers at the time. In 2013, the Chinese partner quit the $253 million project due to limited demand and economic losses, but in 2017 Liotech closed the fiscal year with its first profits (350 million rubles) [63].

Likewise, to other advanced industrial countries, Russia will soon have a flourishing Li-ion battery industry. Accordingly, the country's nuclear energy company recently announced plans to start mining lithium and develop its own lithium-ion batteries [64].

Though still hosting a significant chemical industry, and even (in Serbia's Jadarone) one of the biggest deposits of lithium in the world in the form of jadarite [65], Europe hosts a few and relatively small Li-ion battery manufacturers. In early 2018, discussion was still ongoing in Germany among automotive, chemicals, raw materials, engineering and energy companies whether to build all together the missing battery production plants [66].

4.2. The hydrogen fuel cell industry

Mostly due to higher cost of fuel cells, a few thousand FC electric cars and buses are currently on the world's roads *versus* several million BEVs.

However, the hydrogen fuel cell and water electrolyser industry lately turned into profitable and rapidly growing businesses with numerous mergers and acquisitions reflecting market consolidation and expanded regional presence across the world.

In 2015, for example, Norway's NEL Asa acquired Denmark-based H2 Logic, a reputed manufacturer of H_2 refuelling stations relying on alkaline water electrolysis [67]. Shortly afterwards, NEL also purchased the world's leading PEM water electrolysis company in the US and created a global leader in hydrogen supply for FCEV [45].

Fuel cells enhance the performance of electric commercial vehicles because they extend range and dramatically decrease refuelling time. Three large carmakers, Hyundai in South Korea and Toyota and Honda in Japan, are currently leading the FC electric car market with second-generation vehicles lately commercialized.

To show the pace of progress, in 2008 one of the first FCEV commercialized by Toyota required 15 min to refill enough pressurized H_2 to drive for 300 miles. In 2015, refilling the new Mirai fuel cell car with H_2 to drive for the same distance required only 3 min [68].

Growth and market penetration will be even more rapid especially now that low amounts of Pt are embedded in the FC stacks powering EVs. Again, to put progress in perspective, Daimler's new fuel-cell model shortly to be commercialized (the Mercedes GLC F-Cell) uses 10 g of platinum per vehicle [69], namely 90 percent less platinum than its previous fuel cell model launched in 2009, and equivalent to the amount of Pt contained in today's automotive catalytic converters in diesel and gasoline cars (2–4 g for average gasoline or diesel vehicle, depending on size and model).

According to Colbow, a leading practitioner of the H_2 fuel cell industry, 'platinum contributes 10 percent–15 percent of the cost of a fuel cell stack today' [70]. This means that dramatic reduction in the cost of FC manufacturing will be achieved on scaling up production through economies of flow in which fuel cell companies will focus on flow, processes and time [71].

Indeed, the first material suppliers of the fuel cells industry are starting to commercialize new technologies easily integrated with high-speed automated production lines that, for instance, allow for continuous production process of coated metal foils, replacing subsequent coating of individual bipolar plates with a single coating system able to produce more than 1 million plates annually [72].

Due to high energy density of compressed H_2, large scale adoption of FC vehicles will start from buses, trucks, trains, and large taxi and commercial fleets cutting through the cost of ownership while ending air pollution. Accordingly, some 60 hydrogen fuel cell trains have already been ordered by Germany's regions to replace diesel-powered trains, whereas H_2-powered heavy-duty trucks are completing real life testing prior to forthcoming large-scale commercialization.

For example, in 2017 Toyota started to test, in the port area of Los Angeles, a hydrogen electric truck using the FC stacks of two Mirai cars [68], namely its hydrogen FCEV produced in Japan at a dedicated production line yielding six cars per day.

The heavy-duty truck undergoing testing in Port Beach has 240 miles of range assured by 40 kg of H_2 stored at 700 bar in four storage tanks made of high-strength plastic wrapped in material reinforced with carbon-fiber, and covered with reinforced plastic (safety tests of the tanks filled with H_2 and then placed in mechanical crushers and bonfires revealed no explosion in any case) [68].

As of September 2018, the truck had already cruised for 7180 miles collecting real performance data feeding applied research efforts [68]. In early April 2018, the California's Energy Commission awarded Toyota and a large oil company \$8 million to develop the first hydrogen refuelling station at the Port of Long Beach [73]. The station will fuel both the heavy-duty truck and public FCEV fleets with renewable hydrogen sourced by an adjacent tri-generation facility producing hydrogen from biogas.

On 3 May 2018, the large US-based beer making company Anheuser-Busch announced to have placed an order for up to 800 hydrogen fuel cell trucks from Nikola Motor Company. With first truck delivery foreseen in early 2020, the trucks should have up to 1200 mile range and 20 min refuelling time [74].

5. Electric vehicles, renewable electricity

The early economically and socially significant uptake of EVs takes place amidst a boom in renewable energy adoption across the world, including massive adoption of distributed generation via photovoltaic (PV) electricity in many countries [75].

This means for instance that owners of PV arrays can charge the batteries of their electric cars with the self-generated electricity. It is enough to install a monitoring system for the control and the management of the electric car charging station, to use all surplus solar PV energy to charge the batteries of an electric car. As soon as more solar energy is generated than is simultaneously consumed, the monitoring system sends an electric signal to the charging station, which then incrementally adjusts the charge current supplied to the car [76]. The more solar electricity is available, at higher charge current the charging will occur. Conversely, if there is less surplus energy, the charge rate decreases.

A further benefit is that by increasing self-consumption, the load on the grid is decreased whereas EVs help to balance intermittent sun and wind power generation by providing a controllable load, which are both critical aspects in light of large-scale adoption of electric cars [77].

Year 2017 has been the first in which the solar PV capacity installed across the world approached the 100 GW threshold (98.9 GW) [78], out of which 52.8 GW in China where the overall PV power connected to the grid in 2017 generated 118.2 TWh (+78.6% increase on 2016) [79].

The transition to electric mobility in countries with high penetration of renewable energy generation results in a synergistic and highly beneficial effect on the overall energy bill paid by the country. In closer detail, increasing the PV generation during the replacement of internal combustion engine vehicles by EVs boosts the economic savings due to the amplification of the impact of the PV generation on the wholesale power market along with the increasing electricity demand [80].

Similarly, in the emerging distributed solar hydrogen scenario [81], renewable hydrogen needed to fuel cells will be produced via water electrolysis with state of the art electrolysers.

The *Energy Observer*, for example, is the catamaran currently undertaking the tour of the Mediterranean basin. All the electricity needed to power the vessel's energy needs is supplied by a 21 kW array of bifacial solar PV modules covering a 120 m^2 surface along the entire length of the hull, and by two 1 kW vertical axis wind turbines [82].

In favourable cruising conditions, batteries are used to cover power demands of the two reversible electric motors (2 $\times$ 41 kW) and for the various energy needs, with power generation and consumption balanced. For long crossings, the propeller starts acting also as a dynamo and the resulting power is used to produce hydrogen from seawater. When solar and wind energy is not enough to meet demand, the hydrogen fuel cell provides the propeller with additional power.

Remarkably, an even larger (100 tonne) solar hydrogen catamaran (*Race for Water*) using the same approach to renewable electricity storage based on solar hydrogen, fuel cell and Li-ion batteries, had already covered by April 2018 nearly 10 000 (9656) nautical miles from the Atlantic to the Pacific Ocean [83].

Now, electricity is generated by 500 m^2 of efficient PV modules in monocrystalline Si able to supply 93 kW of nominal power. The PV power is used to produce nearly 200 kg of hydrogen via electrolysis of desalinated and deionized marine water. Hydrogen leaving the electrolyser at 50 bar is further compressed to 350 bar and stored in cylinders from which it fuels two 30 kW fuel cells.

On large scale, H_2 will be extracted from water either by concentrated solar power [84] or using all surplus power obtained at today's very low cost of generation from grid-connected wind and photovoltaic parks. For example, a set of 24 alkaline 2.2 MW single stack electrolysers with a power consumption of 3.8 kWh Nm^{-3} H_2, using renewable power purchased at \$50/MWh, enables the production of hydrogen at <\$3.5/kg in such amount in one year to satisfy the yearly fuel needs of >55.000 cars or >1000 buses [45].

6. Conclusions

The analysis undertaken for this study at the dawn of the global boom in EV uptake allows us to draw seven main conclusions.

First, supported by well-planned and executed policy including incentives as well as financial support of China's public banks, China has created from scratch in about one decade (2008–2017) the world's largest EV and lithium ion battery industries. Its affordable products, coupled to lower cost of ownership, lack of atmospheric pollution and rapidly expanding charging infrastructure in many countries, are driving large-scale uptake of battery EVs across the world.

Sales of electric cars in France exceeding 4200 units only in the month of March 2018 (after the country installed 12 000 charging points in 2017); delivery to India's Government of the first 10 000 EVs whose cost of ownership is INR 0.85 per kilometer cost against INR 6.5 per kilometer cost for fossil fuel cars; [85] the ongoing construction of huge Li-ion battery factories and the staggering number of electric buses (385 000) which reached the roads of China in less than five years—all point to forthcoming dramatic changes in a well established global market built around its two core technologies: the internal combustion engine, and gasoline and diesel fuels obtained from petroleum in the oil refinery.

Second, more recent progress in hydrogen fuel cell and water electrolysis technology has led to the introduction of the first fuel cell electric cars successfully commercialized in Japan, California and other regions and countries where a significant hydrogen refuelling infrastructure is already in place.

Third, the technical enablers of said progress have been dramatic advances in lithium battery and fuel cell technology and in industrial lean manufacturing of both.

Fourth, the two enabling technologies are complementary with hydrogen fuel cells being particularly well suited for heavy-duty and long range transportation as the first 60 hydrogen fuel cell trains recently ordered in Europe clearly demonstrate.

Fifth, forecasts of raw material shortage and forthcoming high prices should not deter investment in lithium battery technology and hydrogen fuel cells. Similar forecasts on 'intrinsic' production costs of crystalline silicon led many to believe that the PV technology was doomed to failure with the end of the feed-in tariff incentives. In 2016, PV energy became the fastest-growing energy source worldwide and today, driven by its exceptionally low cost, the deployment of new PV power generation grows at >100 GW per year.

Lithium is abundant and as of late, the first Li battery recycling plants started operation in Japan and in China. The use of cobalt in cathodes can be avoided though as suggested by Narins [60], it will be enough to restore balance between production and consumption to ensure decades of prolonged lithium availability at affordable cost. Similarly, the amount of platinum in today's fuel cell cars is comparable (10 g) to that contained in a typical autocatalyst (2–4 g), and will continue to decrease steadily, whereas progress in chemistry has already resulted in the first alloyed carbon catalyst replacing platinum in commercial fuel cells (though not yet of sufficient power for use in FC vehicles).

Sixth, forecasts of 'exceedingly high cost' for countrywide hydrogen refuelling infrastructure should not deter investment in water electrolysis or hydrogen fuel cells manufacturing. A network of only 328 hydrogen refuelling stations, mostly located in Japan, California, Germany, and Switzerland has been enough to cause the first burst in the number of fuel cell cars and buses on roads. One single H_2 refuelling station factory based in Europe already has the capacity to manufacture 300 hydrogen stations annually.

Seventh, all main industrially advanced countries will quickly develop their own EV industry, including the two enabling technologies: the lithium battery and the hydrogen fuel cell.

Acknowledgments

This article is dedicated to Professor Athanasios Konstandopoulos, Centre for Research and Technology-Hellas, for all he has done for the progress of solar hydrogen production via sunlight-driven thermochemical water splitting.

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