Applications of Fuel Cell Technology: Status and Perspectives

by Jürgen Garche and Ludwig Jörissen

About 175 years have passed since the invention of the fuel cell (FC) by Schoenbein und Grove,[1] but up until now, only limited market penetration has occurred despite the potentially high energy conversion efficiency of FC technology. The very successful development of electrical generators and internal combustion engines (ICE) for cars and the challenges related to material selection and electrode kinetics led the promise of the fuel cell to almost sink into oblivion in the initial century or so since its invention.

In the first half of the 20th century, there were isolated attempts to develop FCs, such as by Francis T. Bacon, who started his alkaline fuel cell (AFC) development in 1932 and presented a practical 5 kW system in 1959. In the same year, Harry K. Ihrig (Allis-Chalmers) demonstrated the first FC vehicle, a 15 kW AFC powered tractor (Fig. 1).

Fig. 1. *15 kW AFC-powered tractor of Allis-Chalmers. (From the National Museum of American History, Science Service Historical Images Collection, courtesy of Allis-Chalmers.)*

In the 1960s and 1970s, FCs found application in the space program (AFC-Apollo, and polymer electrolyte fuel cell (PEFC)-Gemini). However, this development occurred without substantial impact in the civil sector. Abundant availability of energy further stood against FC commercialization. Only with the first oil crisis in the beginning of 1970s, was energy efficiency again addressed, causing an increase of FC development activities in the years to follow.

However, in spite of all these developmental activities, no commercial market was found for FCs. In the beginning of the 1990s, global environmental and resource problems as well as related legislation, such as the Clean Air Act and Zero Emission Mandates in California, drove the automotive industry to develop electric vehicles (EVs), also powered by FCs. In 1997, Daimler-Benz announced the commercial market introduction of FC-EVs for 2004. Although this date was considered to be about 10 years too early, its announcement triggered a renaissance in FC development. Nearly all car manufacturers worldwide started FC-EV development programs after 1997, leading to a huge boost in the fundamental understanding and a concomitant lowering in cost. Today, FC costs are still considered too high for unsubsidized commercialization. Promising developments have taken place aside from light-duty road vehicle application; examples include FCs for residential combined heat and power (CHP), propulsion of forklifts, generation of backup power, and off grid and portable power. This large progress and optimistic attitude in the PEFC area was transferred also to other FC technologies although the technical overlap with the phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), and solid oxide fuel cell (SOFC) is low. The euphoric period created in the beginning of the new millennium, however, did not lead to wide market penetration of FC applications. Disillusionment followed almost till the end of the first decade of the 21st century. But subsequently, the large R&D efforts in place for two decades are bearing the first fruits as shown in Table I.

Table I. Market development 2009–2014 for different applications based on shipments (pieces) and power (MW). **Uncorrected Fuel Cell Today forecast from 2013*[2]*.*

Shipment by application						
	Fuel Cell Today (as published)					Forecast
1,000 Units	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Portable	5.7	6.8	6.9	18.9	13.0	21.8
Stationary	6.7	8.3	16.1	24.1	51.8	45.6
Transport	2.0	2.6	1.6	2.7	2.0	2.9
Total	**14.4**	**17.7**	**24.6**	**45.7**	**66.8**	**70.2**

Megawatts by application						
	Fuel Cell Today (as published)					Forecast
Megawatts	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Portable	1.5	0.4	0.4	0.5	0.3	0.5
Stationary	35.4	35.0	81.4	124.9	186.9	147.3
Transport	49.6	55.8	27.6	41.3	28.1	28.2
Total	**86.5**	**91.2**	**109.4**	**166.4**	**215.3**	**176.0**

Of the total fuel cell megawatts for 2014, the distribution mainly revolves around PEFC (~70 MW), MCFC (~70 MW), and SOFC (~32 MW).[2] About 80% of the power was delivered by Fuel Cell Energy (FCE) and Bloom Energy for the stationary industrial market, Panasonic and Toshiba for the residential CHP market, and Plug Power for the material handling market. In 2013, worldwide fuel cell industry sales surpassed $1 billion for the first time, reaching $1.3 billion.[3] As of 2015 more than 100,000 residential CHP-installations are operative in Japan.

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Whereas the FC and H_2 technology development was driven mainly by industry, these technologies are now included in national energy and environmental programs. Practically in all applications, FCs are competing with well-established technologies (heat engines, batteries, etc.). Because the costs of these competing technologies are determining the market accepted price, FCs initially will substitute the most expensive rival technologies.

Which Fuel Cell for Which Application?

The working temperature (T) of the fuel cell, which is governed by the electrolyte, determines:

- *efficiency* η: with increasing T the internal resistivity and polarization is decreased, which overcompensates the T-dependent voltage decrease
- *start-up time*: time to reach the optimal operating temperature, which increases with increasing T
- *dynamic behavior*: load changes lead to temperature changes and changes (expansions/contracions) in the stack material, resulting in mechanical stress, which gives rise to lifetime reduction. This is especially true in high temperature (HT) FCs with their ceramic components.

These parameters give a first indication to the possible applications of FC technologies. For large stationary applications, we need systems with high efficiency; start-up time and load-following dynamics are a secondary consideration, and normally the MCFC or SOFC would be preferred. For mobile and portable applications, the primary parameters are short start-up time (even from temperatures below 0 °C) and high load-following dynamics, and hence here the PEFC is the system of choice.

A further selection parameter for FC technology is the available fuel. From the electrochemical point of view, hydrogen is the best fuel as its direct reaction gives high system power density, but using hydrogen leads to logistic challenges in fuel supply. Therefore liquid fuels are preferable. Among liquid fuels, methanol reacts directly electrochemically at reasonable rates, however, with much lower power density than a direct hydrogen FC (<20% of H_2). Most other liquid fuels, as well as natural gas (NG) must be converted via reforming to a H_2-rich gas. However, due to a dense NG network, natural gas is widely available.

The hydrocarbon reforming process produces catalyst poisons such as CO, which is thermally desorbed with increasing fuel cell operating temperature. So HT-FCs are less complex, given their easier fuel management.

Fuel Cell Applications

Portable Applications

The definition of portable fuel cells is not very precise. A general definition is that portable FCs encompass those FCs designed to be moved, including auxiliary power units (APU) of lower power. The portable applications range in the power requirement from 25 W to about 5 kW. These FC applications are mostly not driven by energy efficiency (see Table 1), but rather by reduction of noise and emissions, and enhancement in device operating time. Military applications are a special field of portable FCs applications.[4]

Consumer applications ▸ This market covers mainly the 4C applications (Computer, Cordless Phone, Camera, Cordless Tools). Power supplies for notebooks and mobile phones are based on DMFCs and H_2-PEFCs in the power region of ~5 W and 75 W. Demonstrations for notebooks have been developed by Toshiba, NEC, Hitachi, Panasonic, Samsung, Sanyo and LG (50–250 cm³, 10–75 W mostly driven direct by methanol)[5].

Up to now, there are no commercial products for 4C applications. Due to the tremendous progress achieved in Li-ion batteries (e.g., Panasonic NCR18650B, 691 WhL^{-1}, 266 $Whkg^{-1}$), it is difficult to see commercialization of FCs for the mobile computer market. Nevertheless, external chargers for low power electronic devices such as mobile phones, tablet computers etc., are currently on sale. Examples are the MiniPak Charger (Horizon), PowerTrekk (myFC), and Upp Fuel Cell (Intelligent Energy). These typically contain PEFCs: 2–5 W, 5 V USB, priced at $100–$230, weighing120–235 g, and are fueled by H_2-catridges based on metal hydride (MH) and water activated NaSi. A portable liquid propane gas (LPG)-fueled micro-tubular SOFC (eZelleron) with a start-up time of <1 min and power density >0.3 kW/kg is also under development. In all these cases, devices based on Li-ion batteries are strong competitors due to their comparatively low cost. A 38 W-h Li-ion battery USB charger costs approximately $50, and has a weight of 272 g.

Power Supply for Recreational Vehicles and Specialty Markets ▸ These markets comprise long term power supply applications such as caravans, RVs, sailing boats, energy supply for remote sensor or relays stations etc., with restricted site access. Due to the enhanced functionality of the application, the current high prices of FC systems are acceptable. However, for these markets, the availability of a fuel that can be easily transported (such as methanol) or that is easily accessible worldwide (such as LPG) is important. SFC Energy AG has sold more than 31,000 DMFC systems (40 W, 72 W, and 105 W for approximately $2,800, $4,300, and $5,900 respectively), both for leisure and industrial applications.

To avoid challenges related to gas processing, systems powered by LPG or higher alcohols frequently are based on high temperature PEFC technologies such as those developed by EnyMotion (EnyWare B500, 500 W using bio ethanol), Truma (VeGA, 250 W using LPG), or on SOFC technology such as the LPG-powered RP-20 system from Acumentrics (500 W, start-up time <1 h).

Stationary Applications

Included in the stationary FC market are the core applications such as prime power, large CHP, residential CHP (resCHP), and uninterrupted power supply (UPS). Tri-generation systems are under development for heat, power, and cooling (via an added absorption chiller), particularly for areas where the thermal demand during the cold season is balanced by an almost equal cooling demand during the hot season.[6] Furthermore, oxygen depleted air from the fuel cell exhaust can be used for fire prevention.

A strong driver for several of the stationary applications is “resilience,” which reflects the ability of a system to absorb unexpected events (such as blackouts) via distributed power plants for grid stabilization and backup. The stationary FC sector represented >70 % of global FC revenue in 2014, and is expected to continue to lead the overall FC market in the coming years. According to a recent report from Navigant Research,[7] annual shipments of stationary FCs will grow from nearly 40,000 in 2014 to 1.25 million in 2022 (CAGR = 51.7 %).

Industrial Applications ▸ The main applications for the industrial use of FCs are prime power, CHP, and tri-generation, mainly for new office builds, retail parks, hospitals, universities, or data centers. Because of the higher electrical efficiency of HT-FCs, MCFCs and SOFCs are usually used for such applications. PAFCs, PEFCs, and recently AFCs have been used to a lesser extent. Furthermore, the reduced gas reforming effort in HT-FCs allows using biogas from landfills, biomass, and digester sources to be used as fuel. Natural gas, however, is the dominant fuel. The prime power market of large stationary fuel cells is led by three players — Bloom Energy, FCE, and ClearEdge Power (now Doosan).

MCFC — Fuel Cell Energy, based in the U.S., with its subsidiary, Fuel Cell Energy Systems (FCES) in Germany, and with its close relationship to POSCO (South Korea), is the main player in this market, delivering MCFC modules since 2007. Their main MCFC products are: DFC 300–300 kW_{el}, DFC 1500–1,400 kW_{el}, DFC

3000–2,800 kW_{el} with η_{el} (LHV) = 47 ± 2% and η_{total} = 90%. FCE's production capacity for MCFCs will be soon 100 MW/annum. From 2015, POSCO, however, will produce modules by itself under license from FCE, at a planned capacity of 100 MW/annum.

MCFC plants are in operation in more than 65 sites worldwide. An 11.2 MW plant was installed at Daegu City (South Korea) and a 14.9 MW plant in Connecticut (U.S.). The world's largest FC plant (Fig. 2), a 59 MW facility, is being built in Hwasung City (South Korea), which is part of an upcoming 122 MW MCFC park. Additional large parks have been proposed for the Seoul region (230 MW_{el}) and Pyeongtaek city (multi-hundred MW_{el}).

The cost to manufacture a MCFC plant today is approximately \$2,500–\$3,000/kW_{el} with the goal being to to decrease it to \$1,500/kW_{el} by increasing the module lifetime to greater than five years and by lowering the cost of fuel processing. A quasi-stationary application of MCFCs is their installation on board ships. The EU Fellowship project is an example of this application, with a 2.8 MWe MCFC.

SOFC—After Siemens-Westinghouse stopped their activities at the end of the 2000s due to high costs (>\$17,000/kW) and limited lifetime, only Bloom Energy is serving the market for large SOFC systems. The ES-5000, ES-5400, and ES-5700 systems were developed, generating 100 kW_{el}, 105 kW_{el}, and 210 kW_{el} respectively. All systems are based on a 1 kW_{el} stack (40 cells of 25 W_{el} each) and $\eta_{el} \approx 50\%$. Specific system costs are between \$7,000–\$8,000/kW (@ 100 kW_{el}). In 2013, a 6 MW (30 Bloom 200 kW_{el} systems) CHP plant was opened at e-Bay's data center in Utah (U.S.).

PAFC[8] — Based on the early ONSI PC 25 (200 kW_{el}, η_{el} = 40 %, ηtotal = 84%, \$4,000/kW), UTC developed the NG-powered 400 kW_{el} PureCell system (η_{total} = 95%) in 2009. 4.8 MW plants were built by combining 12 Pure Cell Systems for GS Power/Samsung (Anyang, South Korea) and the World Trade Center (in NYC). In 2013, UTC was taken over by ClearEdge and subsequently by the Doosan Group in 2014. A further player is Fuji Electric, which has produced, since 2009, the FP-100i system (100 kW_{el}, η_{el} = 40%, η_{total} = 87%, \$13,000/kW) driven by NG or LPG. The annual production rate is on the order of 2 MW_{el}.

Residential applications ▸ Residential CHP units produce heat and power mainly for single-family houses. In comparison to conventional CHP technologies (ICE, Sterling Engine) FC systems lead to significant reductions in CO_2-emissions (about 1–2.5 tons/annum/house).[9] NG is primarily used as the fuel for residential CHP applications. Both PEFCs (quick start-up, power modulation, direct hot water) and SOFCs (high η_{el}, internal reforming, high temperature heat) are used for this application.

Japan is in a leading position in this domain, and market introduction for residential CHP FC systems has already taken place. Worldwide, about 20 manufacturers are offering CHP systems in the power range from 0.5–5 kW, having an electrical efficiency of 30–40% (PEFC) and 40–60% (SOFC) and η_{total} > 85%. The heat-to-power ratio amounts to 2 (PEFC) and 0.5–1 (SOFC).

The world's most successful program for resCHPs is the Japanese Ene-Farm project that started as far back as 1990. With the help of government support, about 105,000 units (700–750 W each, $\eta_{total} \approx 95\%$) have been installed by September 2014. PEFC units are operating continuously and in transient mode, according to the buildings' heat demand, whereas the SOFC works continuously. The Japanese targets are 1.4 million units by 2020 and 5.3 million units by 2030. The target costs for CHP residential FC systems are around \$1,000/kW. The sale prices are currently, however, much higher. Even in the longer run (by 2020), it is projected that only \$3,000–\$5,000/kW will be achievable for 1–2 kW systems.[10]

FIG. 2. *59 MW Gyeonggi Green Energy fuel cell park in Hwasung City. (Courtesy of Fuel Cell Energy.)*

Back-up and off-grid Power ▸ FC systems for back-up and off-grid applications are quite similar, with the exception of the fuel tank capacity; back-up systems for emergency use need lower fuel capacity. Back-up systems are used for areas as server banks, data centers, telematics, traffic controls, tunnels, mines, hospitals, environmental protection, pipelines, disaster control, IT, tele-communications, or signaling. In contrast to the competing battery technologies, FCs decouple energy and power. Furthermore, they have a longer lifetime, lower service requirements, and lower operating costs than batteries and do not suffer from self-discharge. Moreover, due to the short operating time of power backup systems, FC-durability issues are less important compared to CHP-applications.

Typical FC backup power units for telecom applications are in the range of 2 to 10 kW. The fuel capacity on site of such applications must be large enough to cover the required autonomous operation time, which can amount to several days of continuous operation. While secondary batteries are providing a viable solution for autonomous operating times less than 15 h, fuel cell systems require less installation space and are becoming more cost efficient for extended backup times since power generation and energy storage are decoupled. H_2-PEFC systems are primarily used for backup power generation, while reformate-fueled systems or DMFCs are preferred for off-grid power generation or in regions with frequent power outages.

Commercially available PEFC systems include units from Axane (0.5–10 kW), Ballard (1.5–11 kW), Power Cell (3 kW), Electro Power Systems (1.5–10 kW), Heliocentris (1.2–20 kW), Horizon (0.1–25 kW), Hydrogenics (2–200 kW), and ReliOn-Plug Power (0.2–17.5 kW). Systems generating H_2 on site from renewable sources and electrolyzers are also under development, with examples including ElectroSelf TF (1.5–10 kW) and the MF-UEH Series (1–3 kW).

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Transportation

The advantages of FC-based vehicle propulsion include zero-distributed emissions, and far greater well-to-wheels efficiency than ICE or battery vehicles. Compared to battery-EVs, the FC-EVs have a higher range and a shorter refueling time on the order of a few minutes. Because of the short start-up times and the highly dynamic load demand required in vehicle propulsion systems, PEFCs are used as the technology of choice. Despite the limited availability of filling stations, compressed hydrogen at 350 and 700 bar is the fuel of choice. On-board processing of liquid fuels such as methanol, LPG, gasoline, or diesel to yield hydrogen is deemed unfeasible for this application.

The transportation application is mainly concentrated on passenger cars, buses, and material handling vehicles. There is also work on light traction vehicles (golf cars, wheel chairs, airport carts, etc.), bicycles, motorcycles, ships, airplanes, trams, and locomotives. PEFC technology powered by H_2 and O_2 has successfully been used in military submarines, allowing silent slow cruising for up to three weeks without surfacing.

Cars ▸ Passenger cars powered by fuel cells have successfully been demonstrated starting from 2004. Most of the initial development problems, such as start-up from sub-freezing temperatures and range, have been solved. Vehicles today have demonstrated about 3,000 hours (dependent on speed: 150–300 thousand kms) of operation. Start-stop operation and steep transient load cycling (leading to water management and gas transport problems) have primarily affected the lifetime of these FC systems.[11] These and other durability issues are poised to be solved.

High costs, however, are still a major problem despite significant cost reduction that has been achieved over the last few years. Cost calculations done under a DoE contract for a 80 kW PEFC systems under mass production (500,000 units/annum) amounted to \$55/kW in 2014 and are expected to be \$40/kW in 2020; the ultimate target cost is \$30/kW.[12] It was shown that the onset for strong cost reduction started at about 30,000 PEFC units. This is a high number for the market introduction phase. Therefore, car manufacturers are forming alliances to alleviate the burden (such as Daimler, Nissan, and Ford who will produce PEFC Stacks together from 2017 onwards).

A number of automobile manufacturers are now launching fuel cell vehicles. In 2014, Hyundai started an innovative worldwide leasing program of their ix35 car. Toyota and Honda have launched FCEVs in 2015. The Toyota MIRAI FC-EV (described in the article by T. Yoshida and K. Kojima in this issue of *Interface*) has a 100 kW PEFC stack with a power density of 3 kW/liter (2 kW/kg), and is fueled by two 700 bar H_2, tanks allowing a range of 650 km. The system is hybridized by a 1.6 kWh Ni-MH battery that is also used for regenerative braking.

The application of FCs in vehicles is among the most challenging applications from both the performance and cost perspectives. While the necessary performance has been demonstrated, the cost of the FC vehicles is still comparatively high; this is frequently attributed to the high cost of Pt. However, significant progress has been achieved in the recent past. In 2013, Toyota reported a total Pt demand of <30 g (compare against a catalytic converter at 4–7 g Pt)[13] for a vehicle propulsion system. This would amount to less than 3% of the sales price foreseen in U.S. (about \$57,500) or Europe (about \$86,000).

Bus ▸ Transit buses are one of the best early transportation applications for FCs. Buses are highly visible. They operate in congested areas where reduction of air pollution is a key challenge. Operation of fuel cell powered buses is made easier since buses are centrally located and fueled. Furthermore, compared to passenger vehicles, there is more integration space available for the fuel cell system and for the H_2 tanks. Their cost often is mitigated by government subsidies. The first concept buses were introduced in the early 1990s. Since 1994/1998 methanol-fueled transit buses (30 foot, 50 kW PAFC/40 foot, 100 kW PAFC) have been operated by Georgetown University. Given the faster start-up times and the swifter dynamics of the PEFC, the use of H_2 as fuel is more practicable.

In Europe the following bus demonstration programs have been carried out: Clean Urban Transport for Europe (CUTE) from 2003 to 2006 (27 Mercedes-Benz Citaro buses; 40 foot, 250 kW Ballard PEFC, 40 kg H_2 compressed at 350 bar, range 200 km) and the HyFLEET:CUTE program from 2006 to 2009 (47 H_2-buses, of which 14 were H_2-ICE buses). Additionally, bus programs have been demonstrated in Perth, Beijing, and Iceland. Other efforts have included 3 Gillig buses in California, a 20-bus program started in Whistler in 2009, and a 10-bus program in Hamburg in 2010. Currently, Clean Hydrogen in European Cities (CHIC), a major FC-bus demonstration project, is underway in Europe. The suppliers of the FC buses are currently APTS (60 foot, 125 kW PEFC), EvoBus (40 foot, 120 kW PEFC), Van Hool (43 foot, 150 kW PEFC), Wrightbus/ Bluways (40 foot, 75 kW PEFC), and New Flyer (41 foot, 150 kW PEFC).

Despite technical success, cost remains a key challenge. A 40 foot FC bus costs \$1.5–\$2.0 million, compared to an equivalent diesel bus at about \$350,000. The U.S. National Fuel Cell Bus Program (NFCBP) set a cost target of \$600K for a FC bus in 2006–2012. Costs ranging around \$400K–\$600K are expected for 2018–2022, mainly driven by manufacturing breakthroughs and high-volume manufacturing.

Material handling systems ▸ In transportation applications, the greatest commercial activity has occurred in the materials handling segment, where there is a strong business case for FC use in place of the incumbent technology, lead acid batteries. Forklifts are a key target application. Lower operating costs (FCs at \$1,100/year versus batteries at \$ 8,750/year) resulting from shorter refueling

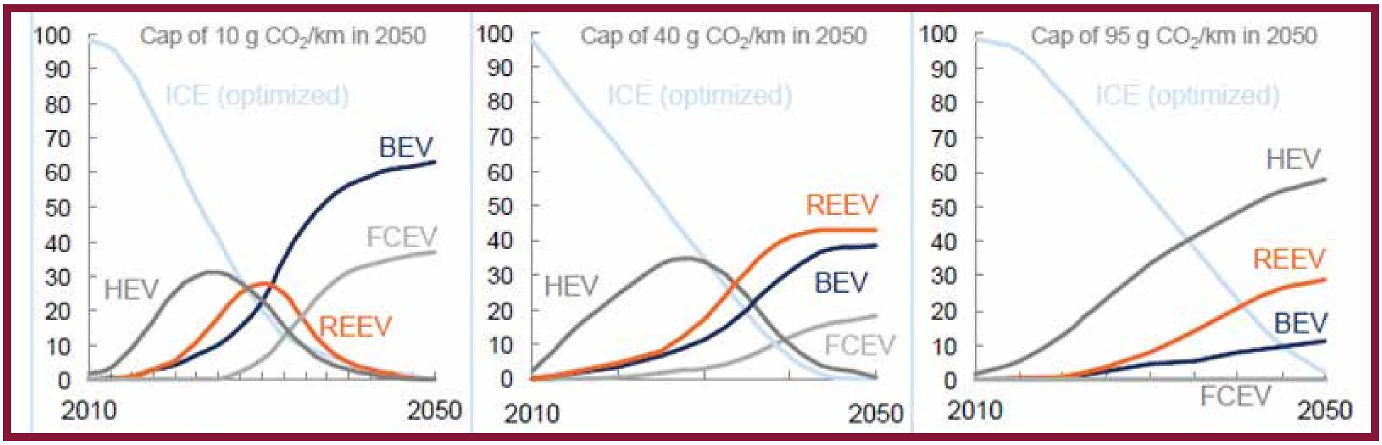

Fig. 3. *Market share development of different electric vehicles (BEV: Battery EV; FCEV: Fuel Cell EV; HEV: Hybrid EV; REEV: Range extender EV) in relation to the Internal Combustion Engine (ICE) for three CO_2 emission cap scenarios in 2050.*[14] *(Coutesy of McKinsey.)*

time compared to battery changing (FC 4–6 min/day, battery 45–60 minutes/day) are key drivers for this application. Furthermore, two batteries (one working, one to be charged) as opposed to only one FC are needed for each forklift. In 2013 approximately 4,000 FC vehicles were operated in the U.S. in large warehousing and distribution centers. The FC systems were mostly produced by Plug Power, Inc. Both are in the demonstration phase. PlugPower offers PEFC systems called Gendrive rated at 3 kW to 14 kW for different applications (e.g., lift trucks, pallet trucks, tow tractors, automated guided vehicles), with an installed fuel capacity of 0.7–3.4 kg H_2 at a pressure of 350 bar. The success of fuel cell-powered forklifts and lift trucks in the U.S. has led to several small demonstration projects in Europe, including the HyLIFT-DEMO and HyLIFT-EUROPE projects, co-funded by the FCH JU.

Outlook

Fuel cell technology has proven its technical viability in several domains of application such as CHP, remote and backup power generation, and vehicle propulsion. Challenges in terms of adequate power density have successfully been addressed, as have durability issues specific to most applications. But costs relative to incumbent technologies are still too high. A considerable further R&D effort is needed to lower costs.

The intensity of industry-promoted R&D is crucially dependent on how various governments support the market introduction of FC technologies by providing favorable regulations with respect to emission control and the use of energy resources, even without providing direct subsidies. As an example, the consequences of legislative action to the vehicle fleet can be seen from Fig. 3.

It is obvious in this case that only strict regulations ($\leq$10 g CO_2/km) leads to a strong FC-EV and battery-EV market in 2050.

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