Roland Berger

Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities

Consolidated Technology Introduction Dossiers

Brussels and Frankfurt, September 2017

Contents

A. WG1: "Heavy-duty transport applications"

Working Group 1 addresses three types of FCH applications (incl. some variants within): trains, trucks and buses

Working Group 1: Heavy-duty transport applications

1. Trains – "Hydrails"
2. Buses
3. Heavy-duty trucks

43 regions & cities are part of the Working Group 1 from **15** European countries

20 industry participants are now part of Working Group 1 from **6** European countries

VDL Bus & Coach
BOC
CALVERA Hydrogen
BMW GROUP
ITM POWER
TOYOTA
Air Liquide creative oxygen
SEIYA consulting
BALLARD
Nedstack
DAIMLER
ALSTOM
Symbio
PLUG POWER
uniper
HYDROGENICS
EvoBus
H2B2
THE LINDE GROUP
HOLTHAUSEN GROEP

Source: Roland Berger

Fuel cell hydrogen trains ("Hydrails") are a future zero-emission alternative for non-electrified regional train connections

Fuel cell electric trains – Hydrails[1]

1/4

Brief description: Hydrails are hydrogen-fuelled regional trains, using compressed hydrogen gas as fuel to generate electricity via an energy converter (the fuel cell) to power traction motors or auxiliaries. Hydrails are fuelled with hydrogen at the central train depot, like diesel locomotives

Use cases: Cities and regions can especially deploy hydrails on non-electric tracks for regional train connections to lower overall and eliminate local emissions (pollutants, CO_2, noise); cities and regions can – for example – promote FCH trains through demo projects or specific public tenders

Fuel cell electric trains – Hydrails (based on Alstom prototype)

Key components	Fuel cell stacks, air compressor, hydrogen tank, electronic engine, batteries
Output	400 kW FC, hybridized with batteries
Top speed; consumption; range	140 km/h; 0,25-0,3 kg/km; 600-800 km
Fuel	Hydrogen (350 bar)
Passenger capacity	300 (total) / 150 (seated)
Approximate unit cost	EUR 5-5.5 m (excl. H_2 infrastructure)
Original equipment manufacturers	Alstom
Fuel cell suppliers	Hydrogenics
Typical customers	Public transport authorities, regional train operators
Competing technologies	Diesel, diesel-electric hybrid, pure battery trains

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1) Focus on FCH-powered regional trains, not considering FCH trams, shunting locomotives, etc.

Source: Roland Berger

Currently, Alstom is testing its Hydrail prototype with two trains in the iLint demonstration project in Germany

Fuel cell electric trains – Hydrails

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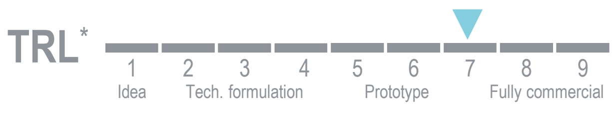
Overall technological readiness: Overall TRL at ca. seven, i.e. mature prototype; rising technical maturity of larger-scale fuel cell modules to be used in trains or tram cars; small scale roll-out in Germany and China in first major "real-life" demonstration projects to prove technical viability and further refine the technology with the help of all stakeholders involved (train operators, network operators, OEMs, etc.)



Demonstration projects / deployment examples / funding schemes for future projects (selection)

Project	Country	Start	Scope	Project volume
Alstom partnership with Landesnahverkehrsgesellschaft Niedersachsen – iLINT	🇩🇪	2017	Testing of 2 fuel cell powered iLINT trains manufactured by Alstom on the route Cuxhaven-Buxtehude (220 km return) in northern Germany, first operation as part of the regional network to start end 2017 / early 2018 – then for two years	n.a.
Shift2Rail	🇪🇺	2015	EU agencies and bodies supporting research and innovation in railway sector through Horizon 2020 grants for zero-emission technologies – link to Single European Railway Area (SERA), funding scheme for future projects	n.a.
Fuel cell hybrid railcar testing by East Japan Railway Company	🇯🇵	2008	Research and development of fuel cell system within "NE-Train" (two 65 kW PEM fuel cells and 19 kWh lithium ion batteries); tests focusing on performance, environmental impact and hydrogen supply; development refocused in 2009 towards battery driven electric units	n.a.

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
iLint	Alstom ALSTOM	Pre-commercial phase of first fuel cell (Hydrogenics) powered regional train. Matching performance of regular diesel trains, Alstom offers a single-source package including train delivery, maintenance and hydrogen infrastructure	🇫🇷	2017	n.a.
KuMoYa E995-1	Tokyu Car Corporation[1]	Prototype hydrogen fuel cell train; development changed to battery electric unit	🇯🇵	2006 / 2007	n.a.

[1] now: Japan Transport Engineering Company

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Hydrails are particularly promising for non-electrified regional tracks where they offer large environmental and social benefits

Fuel cell electric trains – Hydrails

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Use case characteristics

Stakeholders involved

- Regional train operators, regional transport authorities
- Rolling stock OEMs as well as operation and maintenance providers, fuel cell suppliers
- Hydrogen suppliers and infrastructure providers
- Permitting and licensing authorities

Demand and user profile

- Typically non-electrified routes (e.g. 40-50% of infra.in Germany) as part of regional networks (i.e. 100-200 km per route, several cycles per day and train with total required range of up to 1,000 km, speed of 140 km/h)
- Differing topographic profiles (e.g. tunnels of 5-10 km each) and large number of stops/stations (15-50)

Deployment requirements

- Supply infrastructure able to supply large quantities of hydrogen per day, e.g. through local production
- Hydrogen storage, regional/ local distribution networks
- Network of hydrogen refuelling stations along relevant train routes, i.e. in train depots

Key other aspects

- Elimination of need for engine idling at train stations due to fuel cell auxiliary power units (contrary to diesel units)

Benefit potential for regions and cities

Environmental

- Zero tailpipe emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2)
- Lower noise pollution (depending on speed and track conditions reduction of overall noise emissions)

Social

- Increased passenger comfort through reduced noise and vibration, fewer adverse impact on neighbouring communities
- Public health benefits (esp. urban areas near tracks/station), reduced social security expenses, higher standard of living

Economic

- Avoiding cost of future electrification of several million EUR investment per km (i.e. power generation, transformers and transmission lines as well as service disruption caused by overhead wire installation)
- Maintenance and other OPEX savings vis-à-vis operations with diesel-locomotive, long-term savings potential in TCO[1]

Other

- Flexibility to move into service areas not covered by electrification (for industry-stakeholders involved)
- Significant innovation and high visibility potential as flagship/lighthouse projects

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[1] Total Cost of Ownership

Source: Roland Berger

The single-prototype demonstration and potential regulatory/ permitting challenges need to be addressed in the short-term

Fuel cell electric trains – Hydrails

4/4

Hot topics / critical issues / key challenges:

> **Hydrogen infrastructure and supply,** distribution logistics, local storage and refuelling stations, e.g. from an infrastructure-permitting and distribution perspective, but also local availability of large-enough quantities of hydrogen (e.g. from chemical production facilities or large-scale electrolysers)

> **Selection of use cases and suitable routes**, required reassessments of individual train deployment cycle and other necessary performance

> **Technology readiness,** as systems still in advanced prototype phase, e.g. need to extend range from 600-800 km to 1,000 km like diesel trains today

> **General compliance with EU-level and national rolling stock regulations/permitting procedures**, potentially lack or insufficiency of applicable regulatory norms; possibly cumbersome and uncertain rolling-stock approval procedure, need for long-term planning

Further recommended reading:

> Alstom Coradia iLinit product sheet: Alstom Coradia iLinit

> Case Study concerning rail transportation by hydrogen: Rail transportation by hydrogen vs. electrification – Case Study for Ontario, Canada 2: Energy Supply and Distribution

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Fuel cell heavy-duty trucks offer a zero-emission alternative for road-based logistics services, initially likely in a regional context

Fuel cell heavy-duty trucks

1/4

Brief description: Fuel cell electric heavy-duty trucks are otherwise-conventional multi-ton trucks using compressed hydrogen gas as a fuel to generate electric power via a PEM fuel cell as energy converter – which in turn fuels an electric engine[1]

Use cases: Cities and regions can use/promote fuel cell electric heavy-duty trucks in the fields of (regional) logistics/shipping/ forwarding operations of specialized operators or logistics-intensive industries (e.g. food and beverage retail), construction and/or O&M services especially for infrastructure assets

Fuel cell heavy-duty trucks[1]	
Key components	Fuel cell stack, system module, hydrogen tank, battery (mostly lithium-ion batteries), electric engine
Output	250-750 kW (~340-1,000 diesel hp)
FC efficiency; consumption; range	~50%; 7.5-15.7 kg H_2/100 km; 320-1,300[2] km
Fuel	Hydrogen (350 bar)
Battery	30-320 kWh
Approximate unit cost	n.a.
OEMs	Esoro, Kenworth, Nikola, Navistar, Toyota, Scania/ASKO
Fuel cell suppliers	PowerCell, Hydrogenics, Ballard, US Hybrid, Toyota, NuCellSys
Typical customers / users	Logistics, forwarding and shipping companies, retailer, large industrial corporates with own road logistics
Competing technologies	Diesel combustion, battery EV, hybrid vehicles

1) Focus on full FCH powertrain trucks, not considering fuel cell APU systems etc.
2) Very limited FCH truck prototypes with indicative numbers referring to respective prototypes (~26t) deployed in regional distribution use cases. 1,300 km is a future prospective of announced prototypes, not yet empirically proven

Several prototypes have been and will be developed – Bottleneck of commercially available vehicles is expected to diminish

Status of fuel cell electric heavy-duty trucks

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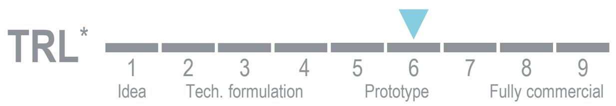
Overall technological readiness: Generally at advanced prototype-stage; prototypes are being (or will soon be) demonstrated in relevant environments, e.g. Esoro FC truck tailored for retailer COOP or ZECT II program; Nikola One FCH truck officially presented in December 2016; further announcement by Norwegian grocery retailer ASKO in 2017 for FCH truck based on Scania and Hydrogenics systems



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope
H2Share	🇪🇺	2018	Production and demo of >12t heavy-duty truck on a DAF chassis and built by VDL. Vehicles to be deployed in DE, FR, BE & NL and used by DHL, Colruyt, Breytner and CURE
ASKO distribution logistics trucks	🇳🇴	2017	Partially gov't-funded demo project to deploy up to 4 FC trucks for regional grocery distribution logistics (~500 km distance); Scania >12t-chassis and Hydrogenics FC
Waterstofregio 2.0/HydrogenRegion 2.0	🇳🇱	2016	Interreg Flanders-The Netherlands funded 40t truck based on DAF CF FT 4x2 modular BE truck with FCH range extension up to ~400km range. Built by VDL & Chassis Eindhoven, demo. starting 2018
COOP distribution logistics trucks	🇨🇭	2016	Due to a lack of fuel cell trucks in serial production, retailer COOP developed a tailored fuel cell truck with OEM Esoro for its regional distribution logistics

Major prototypes (selection)

Name	OEM	Product features	Country	Since
Project Portal	Toyota Motor North America Inc.	Based on a Kenworth T660 chassis with two Mirai fuel cell stacks and a 12 kWh battery; engine with ~500 kW power output and torque of ~1,800 Nm[1]	🇯🇵	2017
US Hybrid FC drayage truck	US Hybrid	Drayage day cab FCH truck based on Navistar Int'l ProStar for regional haul operations; 320/430 kW operating/max. power (Ballard); ~3,750 Nm max. torque; lithium-ion battery	🇺🇸	2017
Esoro FC truck	Esoro	4-wheeled MAN chassis with trailer (total 34 t.); synchronous engine with 250 kW output, stack of 455 fuel cells (PowerCell) with 100 kW output; lithium-ion battery	🇨🇭	2016
Nikola One	Nikola Motor Company	Night cab truck with a range of >1,300 km; engine power output ~750 kW, torque of ~2,700 Nm; Lithium-Ion battery (320 kWh); to be comm. available in several years	🇺🇸	2016

Source: Roland Berger

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

[1] Specifically adjusted to port requirements

The deployment of FC trucks is an attractive option for both public authorities and private companies in order to reduce emissions

Fuel cell heavy-duty trucks

3/4

Use case characteristics

Stakeholders involved

- Users (logistics companies, retailers, etc.)
- OEMs and FC manufacturers
- Public authorities (vehicle approval, regulatory framework of pollutants etc.)
- Hydrogen suppliers and infrastructure providers

Demand and user profile

- Typical road-based regional (or even inter-regional) logistics routes (e.g. between hubs/nodes) of several 100 km in different topographies
- Range, performance and refuelling service offerings ideally similar to conventional diesel-fuelled trucks

Deployment requirements

- Hydrogen refuelling stations (incl. sufficient storage) at nodes (as well as along main shipping routes)
- Maintenance centers at key nodes / truck depots
- High safety standards for FCH components, permitting and licensing of commercial operation

Key other aspects

- Tank size typically needs to at least allow for overnight refuelling (~range of 800 km per day), because of highly regulated working times of drivers (not allowed to refuel in their daily break times

Benefit potential for regions and cities

Environmental

- Zero tailpipe emissions from truck operations (pollutants, CO_2, fine dust particles)
- Potentially lower noise pollution
- Depending on the production type of hydrogen, down to zero well-to-wheel emissions

Social

- Lower adverse health effects associated with road-based transport, especially on communities adjacent to major road-based cargo logistics routes, i.e. highways

Economic

- Potentially lower O&M cost (according to COOP project) and long-term savings potential in TCO[1] depending on fuel prices and reduction of product cost
- Development of expertise in FCEV technology as potential driver of future economic growth

Other

- Depending on the production type of hydrogen, reduction of dependency on fossil fuels or energy imports

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1) Total Cost of Ownership

Source: Roland Berger

Commercial availability, product cost and hydrogen infrastructure are key challenges for large scale deployment of FCH trucks

Fuel cell heavy-duty trucks

4/4

Hot topics / critical issues / key challenges:

- **Commercial availability,** all products now are at prototype stage; most are designed/adapted to service specific use cases
- **Product cost,** capital expenditures expected to be significantly higher as for standard trucks; breakeven point highly dependent on fuel prices
- **Availability of hydrogen refuelling stations (HRS)**, especially challenging for long-distance inter-regional routes (e.g. >500 km); hydrogen storage on the truck or trailer as critical determinant for range – probably in a trade-off with cargo payload space
- **Need for HRS availability** potentially a pointer for initial focus on regional logistics with distances of up to 500 km and relatively fixed routes
- **Environmental sustainability,** well-to-wheel emissions largely depend on hydrogen production

Further recommended reading:

- COOP's world's first fuel cell heavy goods vehicle
- ASKO-Scania FCH truck
- Nicola One by Nicola motor company

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Fuel cell electric buses offer an technologically advanced, zero-emission alternative to the diesel combustion engines

Fuel cell electric buses

1/4

Brief description: Fuel cell electric buses built on a conventional chassis (12-18m) use compressed hydrogen gas as a fuel to generate electricity via the fuel cell (FC dominant powertrains). Other hybrid vehicles e.g. with plug-in batteries or FCH range extenders (larger battery, smaller FC) as well as minibuses are pursued as well

Use cases: Regions and cities can use/promote fuel cell electric buses in all fields of urban public road transport where diesel buses are used today; regions and cities can stipulate zero-emission vehicles through tender requirements for new bus fleets

Fuel cell dominant electric buses (FCEBs)[1]

Key components	Fuel cell module, tank, balance of plant and periphery, battery, e-motor and inverter, mechanical drive line
Output	>100 kW
Efficiency; consumption; range	51-58%; 8-14 kg H_2 /100 km; 250-400 km
Fuel	Hydrogen, 350 bar, ca. 45 kg tank (e.g. total of 3 tanks)
Passenger capacity	Ca. 75-105 (dep. on size and layout)
Approximate unit cost	Approx. EUR 620,000 (upper limit, FCH2 JU JIVE2)[1]
OEMs (selection)	Daimler EvoBus, Van Hool, VDL, Solaris, Toyota, Wrightbus
Fuel cell suppliers (selection)	Ballard, Hydrogenics, UTC Power, NuCellSys (selection)
Typical customers	Municipal public transport operators, (public or private) bus service operators
Competing technologies	Diesel, diesel-hybrid, biofuels/biomethane, CNG, battery EV

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1) Range-extender fuel cell electric buses exist as well
2) Recent industry-based analyses led by the FCH2 JU outline production-at-scale scenarios which see average purchase prices fall to approx. EUR 400,000 over the next ca. 10 years
Source: Roland Berger

There are already large scale deployments of FCH buses in Europe, enabling the transition to a fully commercial application

Fuel cell electric buses

2/4

Overall technological readiness: As one of the most advanced FCH applications, fuel cell electric buses are in a pre-commercial phase with large scale transit-based demonstration projects being currently under way and expected to continue over the coming years

Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Joint Initiative for Hydrogen Vehicles Across Europe (JIVE)	🇪🇺	2017	Large scale deployment of 140+ fuel cell buses across 9 European locations in cooperation with FCH JU; coordinated bus procurement activities	EUR 106 m
3EMOTION	🇪🇺	2015	Deployment of 21 new and 8 existing FC electric buses in several countries all over Europe including the refuelling infrastructure. 6 public transport operators	EUR 41 m
Integration of Hydrogen Buses in Public Fleets (HIGH V.LO-CITY)	🇪🇺	2012	Large scale demonstration of FC buses and refuelling infrastructure addressing key environmental and operational issues, commercial fleets in 3 EU regions	EUR 29.2 m
Clean Hydrogen in European Cities (CHIC)	🇪🇺	2011	Flagship zero emission bus project demonstrating readiness of FC electric buses for widespread commercial deployment	EUR 81.8 m

Recent products / systems (selection)

Name	OEM	Product features	Country	Since	Cost
Citea Electric	VDL	Within the framework of H2busses Eindhoven, deployment of 2 18m tri-axles VDL buses with a trailer where formic acid is split into hydrogen	🇳🇱	2017	n.a.
Urbino 18.75	Solaris	Deployment of first Solaris Urbino electric buses with fuel cell range extender; deployed on Hamburgs "innovation line"	🇩🇪	2014	n.a.
A330	Van Hool	Deployment of 10 13m tri-axles hydrogen buses in Aberdeen, with 50 kg storage capacity, part of strategy to create a hydrogen economy in the region	🇬🇧	2014	n.a.

Source: Roland Berger

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Fuel cell electric buses could help reduce carbon and noise pollution and increase standard of living in urban areas

Fuel cell electric buses

3/4

Use case characteristics

Stakeholders involved

- Customers (public transport operators, bus service operators etc.)
- OEMs and FC manufacturers, H_2 -suppliers
- Public authorities (vehicle approval, regulatory framework for emissions etc.)

Demand and user profile

- Same service of routes and service hours as diesel buses (different topographies, route lengths, total distance travelled p.a.) incl. necessary reliability of operations (e.g. up to 95%) to meet schedules and have full-day continuous operation away from the depot

Deployment requirements

- Hydrogen refuelling station infrastructure – also permitting of inner city refuelling stations close to residential neighborhoods very complex
- Maintenance & repair infrastructure
- Permitting and licensing of commercial operation

Key other aspects

- \-

Benefit potential for regions and cities

Environmental

- Depending on production of hydrogen, zero tailpipe emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2)
- Low noise pollution (depending on speed and track conditions almost no noise emissions at all)

Social

- Public health benefits (esp. in urban areas), overall higher standard of living
- Lower adverse impact on residents adjacent to major inner-city logistics routes, e.g. retail pedestrian areas

Economic

- With CAPEX reduction, increases in efficiency and affordable supply of hydrogen, potential to reduce TCO[1] below battery EV, biofuel and even diesel buses

Other

- High passenger comfort based on deployment experience
- Generally high public / every-day visibility as "urban" FCH use case, FCH flagship potential for regions and cities

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1) Total Cost of Ownership

Source: Roland Berger

As large scale deployments are ongoing, further improvement of technology and reduction of CAPEX/OPEX expected

Fuel cell electric buses

4/4

Hot topics / critical issues / key challenges:

> **Reduction of CAPEX,** mainly through further large scale deployments across Europe

> **Technical performance,** reduction of bus downtimes for costly maintenance (increase of overall bus availability) in order to increase overall utilisation of fleet, efficiency improvements

> **Hydrogen infrastructure,** i.e. distribution logistics, local storage, refuelling stations and respective costs

> **Well-to-Wheel emissions,** reduction potential largely depends on resources used for hydrogen production

> **System integration and range extension,** enlargement of operation range or further development of hybrid operation with battery powered power train for extension

> **Cost of hydrogen,** strongly influences the competitiveness towards benchmark technologies

Further recommended reading:

> FCH2 JU, 2017 – Fuel cell electric buses demnonstation projects deployed in Europe

> FCH2 JU, 2016 – Strategies for joint procurement of fuel cell buses

> FCH2 JU, 2015 – Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe

> EC DG Mobility and Transport, 2017 – Declaration of intent on promoting clean buses deployment

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

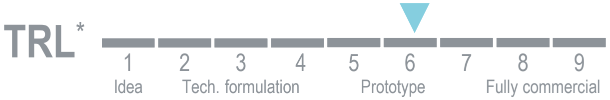
https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Fuel cell minibuses are a smaller, zero-emission alternative to large urban FCH buses with a variety of potential use cases

Excursus: Fuel cell electric minibuses

Brief description: Fuel cell minibuses are a hydrogen-fuelled transport application, using compressed hydrogen gas as fuel to generate electricity via a converter (a low-temp. PEM fuel cell) to power a electric engine – FCH minibus concepts are generally based on FCEV (i.e. car) technology



Use cases: Cities and regions can deploy or incentivise the deployment of FCH minibuses for example in shuttle services (e.g. airports, hotels, resorts, etc.) and public transport (e.g. bus lines with fewer passengers or routes through small villages or inner cities with narrow streets) to increase efficiency and decrease local emissions (pollutants such as NO_x, CO_2, noise)

Existing prototypes and demonstration projects (selection)

Project/product	Country	Since	Specifications
Hyundai H350 Fuel Cell Concept	🇰🇷	2017	Hyundai presented this concept vehicle at the IAA 2016 in Hannover with 2 times 700-bar high-pressure tanks comprising a storage of 7.05 kg of hydrogen and powered by a 100 kW electric motor. The vehicle reaches speeds of up to 150 km/h
Dolomitech Fuel	🇮🇹	n.a.	This vehicle is produced by Dolomitech s.r.l. and is based on an IVECO Daily model and was developed with several partners, including Linde. It is equipped with a 80 kW electric traction motor fuelled by a 7 kg hydrogen tank with hydrogen stored at 350 bar

ⓘ **For additional information regarding fuel cell powered minibuses, please contact our Roland Berger team directly**

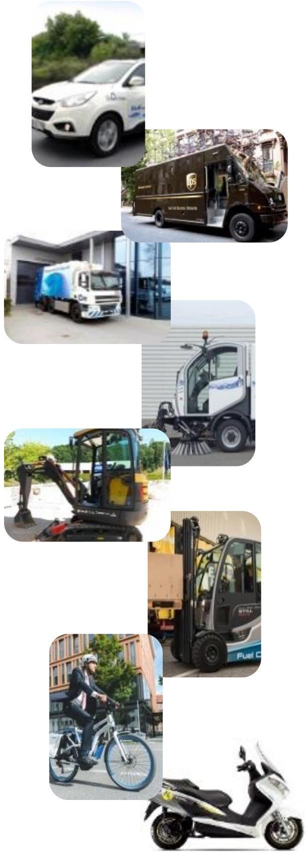
Source: Roland Berger

*) Technology Readiness Level ▼ ≤ 5 ▽ 6-7 ▼ 8-9

B. WG2: "Light- and medium-duty transport applications"

Working Group 2 addresses eight types of FCH applications (incl. some variants within), e.g. cars, delivery vans and forklift trucks

Working Group 2: Light and medium duty transport applications



1. Cars
2. Delivery vans
3. Garbage trucks
4. Sweepers
5. Construction mobile equipment
6. Material handling
7. Bikes
8. Scooters

50 regions & cities are part of the Working Group 2 from

18 European countries

22 industry participants are now part of Working Group 2 from

8 European countries

Source: Roland Berger

Fuel cell electric vehicles offer a viable zero-emission alternative compared to combustion engine cars with similar usability

Fuel cell electric vehicles – Cars

1/4

Brief description: Fuel cell electric vehicles - cars (i.e. passenger cars powered by fuel cells) use compressed hydrogen gas as a fuel to generate electricity via an energy converter (fuel cell) to power an electric motor. FCEV are refuelled at dedicated filling stations

Use cases: Cities and regions can deploy FCH fleets for municipal/community services; additionally, cities & regions can incentivize the adoption of FCEV cars for private or commercial use e.g. through FCEV car-sharing initiatives or local zero-/low-emission zones

Fuel cell electric vehicles (FCEV) - Cars	
Key components	Fuel cell stack, system module, hydrogen tank, battery, electric motor
Output	70-130 kW
Top speed; consumption; range	160 km/h; 0.76-1 kg H_2/100 km; 385-700 km
Fuel	Hydrogen (700 bar)
Battery	1.6-9 kWh (Toyoty Mirai and Daimler GLC F-cell hybrid)
Approximate unit cost	EUR 51,000 - EUR 78,600
Original equipment manufacturers	Audi, BMW, Daimler, Ford, GM, Honda, Toyota, Hyundai
Fuel cell suppliers	BMW, NuCellSys, Honda, Toyota, Hyundai
Typical customers	Private consumer, public-sector and commercial fleet operators (e.g. car sharing, taxi, fleets run by enterprises)
Competing technologies	Gasoline or diesel combustion, battery powered EV[1]

[1] Electric Vehicle

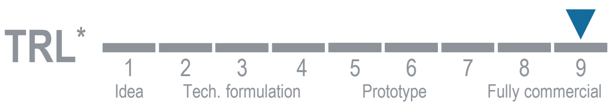
Source: Roland Berger

Three different models are already commercially available; several European car manufacturers are about to follow

Fuel cell electric vehicles – Cars

2/4

Overall technological readiness: FCEV technology is commercially ready with leading OEMs offering selected models in serial production; widespread market introduction depending on expansion of hydrogen refueling infrastructure and economies of scale / learning-curve effects to lower the premium on the product cost



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Hydrogen Mobility Europe (H2ME)	🇪🇺	2016	H2ME brings together eight European countries in order to improve hydrogen refuelling infrastructure and to demonstrate feasibility of over 1,400 cars and vans in real-life operations	EUR 164 m
Hydrogen for Innovative Vehicles (HyFIVE)	🇪🇺	2014	One of Europe's largest transnational FCEV projects deploying 185 vehicles and creating clusters of refuelling station networks to lead the sectors commercialisation	EUR 39 m

Products / systems available (selection[2])

Name	OEM	Product features	Country	Since	Approx. cost
Clarity Fuel Cell	Honda	Highest driving range of any zero emission car, availability only in California markets outside Japan. Only manufacturer which has its FC technology exclusively located in the engine compartment. Heading towards serial production	🇯🇵	2017	EUR 51,000
Mirai	Toyota	Availability in Europe limited to BE, DK, DE, F, N, NL, S, UK	🇯🇵	2014	EUR 78,600
ix35 Fuel Cell	Hyundai	In commercial service by car sharing service BeeZero (Munich, Germany) or world's largest FCEV taxi fleet "HYPE" (Paris, France)	🇰🇷	2013	EUR 65,400

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

2) Selected models commercially available, further market introductions planned by e.g. Daimler (GLC summer 2018), BMW

Source: Roland Berger

Zero tailpipe emissions and lower noise pollutions bear significant FCEV-related benefits for European regions and cities

Fuel cell electric vehicles – Cars

3/4

Use case characteristics

Stakeholders involved

- Private/public consumers/drivers, fleet customers such as municipalities, large private companies, taxis, etc.
- Hydrogen infrastructure operators
- Commercial (urban) car sharing operators
- OEMs as well as maintenance/service providers

Demand and user profile

- Depending on driving patterns and routes, potentially all use cases currently serviced by combustion-engine passenger cars (given similar usability)
- Range, performance and refuelling process of FCEVs similar to conventional cars

Deployment requirements

- Network of hydrogen refuelling stations
- Hydrogen supply and distribution network
- Adherence to high safety standards for fuel cell components
- Permission and licensing of commercial operations

Key other aspects

- Lower battery size, superior operability at low temperatures, longer range and shorter refueling time compared to battery powered EV

Benefit potential for regions and cities

Environmental

- Zero tailpipe emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2), low noise pollution (also depending on model, track conditions etc.)
- Well-to-wheel greenhouse gas emission 25-100% less compared to conv. vehicles, depending on hydrogen supply

Social

- Overall comfort in driving incl. car range, refuelling process at least comparable to combustion-engine vehicles
- Ultimately thanks to low/zero emission footprint: public health benefits and higher standard of living

Economic

- Development of expertise in FCEV technology as potential driver of innovation and future economic growth
- Additional potential revenue streams for public authorities through licensing of FCEV taxis
- Potentially low TCO in the future (low-cost H_2, lower CAPEX)

Other

- Significant reduction of dependency on fossil fuels or energy imports (depending on the type of hydrogen production)

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1) Total Cost of Ownership

Source: Roland Berger

High cost and low overall coverage of hydrogen refuelling stations present key challenges for FCEV deployment

Fuel cell electric vehicles – Cars

4/4

Hot topics / critical issues / key challenges:

> **Guaranteed basic coverage** of hydrogen refuelling stations ensuring usability for consumers

> **High cost for hydrogen and its distributions/storage** as hurdle for overall commercial attractiveness – need for cost reduction in hydrogen supply, e.g. via a higher utilisation of refuelling stations

> Currently **low willingness-to-pay** for FCEV price premium on the side of end customers – hence need to identify fleet operators as anchor customers / early adopters

> Large **potential for cost reduction** primarily driven by economies of scale (higher manufacturing volumes thus critical) but also further innovation to lower material costs (e.g. decrease amount of platinum in fuel cells)

> **Well-to-wheel emission** largely depending on underlying resources used in hydrogen production

> **Compliance** with EU-level and national safety regulations

Further recommended reading:

> Official website of Hydrogen Mobility Europe: http://h2me.eu/

> Official website of Hydrogen for Innovative Vehicles: http://www.hyfive.eu/the-hyfive-project/

> Official website of Clean Energy Partnership (CEP): https://cleanenergypartnership.de/home/

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

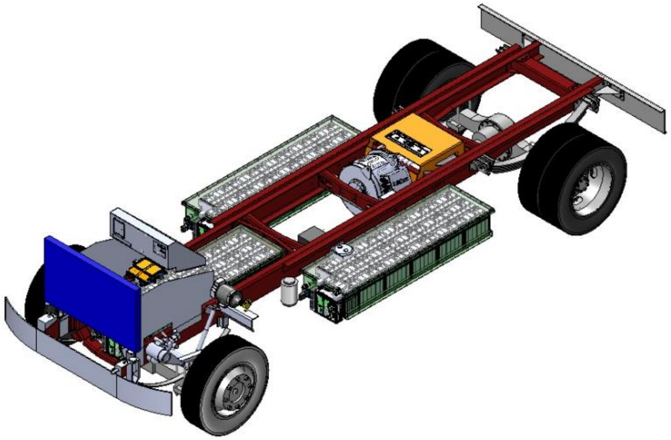
https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Fuel cell powered delivery vans offer a zero-emission alternative for inner-city delivery logistics, e.g. for postal and parcel services

Fuel cell electric vehicles – Delivery vans

1/4



Brief description: Fuel cell electric vehicles (FCEV) delivery vans use compressed hydrogen gas as a fuel to generate electricity via an energy converter (the fuel cell) to power an electric engine – full FCH drive train; hybrid systems with battery and FCH range extenders exist as well and are currently pursued most actively

Use cases: Cities & regions can use/promote FCEV for commercial use in all kinds of inner-city delivery services, e.g. deploy FCH delivery vans for municipal dispatches in order to lower noise and air pollution as well as carbon dioxide; cities and regions can establish "environmental zones" (zero-/low-emission-zones)

Fuel cell electric vehicles (FCEV) – Delivery Vans[1)]

Key components	Fuel cell stack, system module, hydrogen tank, battery, electric engine
Output	45-150 kW (~60-205 hp)
Top speed; range	100-130 km/h; ~200-300 km (2 times 5kg hydrogen tanks)
Fuel	Hydrogen
Battery	22-80 kWh lithium-ion battery pack
Approximate unit cost	n.a.
Original equipment manufacturers	Unique Electric Solutions, Renault/Symbio Fcell, Street Scooter
Fuel cell suppliers	Hydrogenics, PlugPower, Symbio Fcell, NuCellSys
Typical customers	Logistics companies, postal services, other delivery
Competing technologies	Gasoline or diesel combustion, EV[2)] (+ range extender)

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1) Mainly based on two examples: Navistar International 1652SC for UPS in California and Renault Kangoo ZE H2 350b by Symbio

2) Electric Vehicle

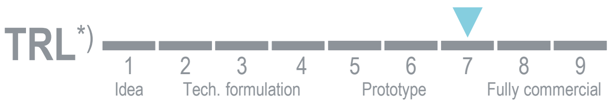
Source: Roland Berger

UPS recently presented another hydrogen fuel-cell powered zero-emission delivery vehicle at ACT Expo 2017 in Long Beach, CA

Fuel cell electric vehicles – Delivery vans

2/4

Overall technological readiness: FCEV delivery vans are still in proof-of-concept phase, use cases are predominantly centered around range extension of existing battery powered vans in commercial use for last-mile deliveries



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Hydrogen Mobility Europe (H2ME)	🇪🇺	2016	H2ME brings together eight European countries to improve hydrogen refuelling infrastructure and to demonstrate feasibility of over 1,400 vans and cars in real life operations	EUR 164 m
Fuel Cell Hybrid Electric Delivery Van Project	🇺🇸	2014	Proof-of-concept for commercial hydrogen powered delivery vehicles as well as performance and durability data collection from in-service operations of 17 fuel-cell vans in collaboration with UPS, funded by U.S. Gov. through DOE	EUR 10.3 m
HyWay1)	🇫🇷	2014	Largest European hydrogen fleet and 2 refuelling stations to test operation of hydrogen-powered range extenders, 50 Kangoo ZE- H_2 in service	n.a.
VULe partagé1)	🇫🇷	2014	Commercial car sharing service in partnership with Paris town hall targeted at merchants and craftsmen; 10 Kangoo ZE-H_2 (range extended) in service	n.a.

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
UPS delivery van	Unique Electric Solutions	Fuel cell powered walk-in van based on Navistar International 1652SC 4x2, 32 kW fuel cell (Hydrogenics HD30), 45 kWh LiFeMgO4 battery (Valence Technology) in California. Similar project of FedEx in the same region	🇺🇸	2014	n.a.

1) Only fuel cell range extender comprised

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Specific use case characteristics matched with demand and user profiles enable promising benefits, esp. on the environmental side

Fuel cell electric vehicles – Delivery vans

3/4

Use case characteristics

Stakeholders involved

- Users (logistic carriers, merchants, craftsmen, postal services, utility providers); public authorities (vehicle approval, regulatory framework of pollutants etc.)
- OEMs and FC manufacturers
- H_2 suppliers and infrastructure providers

Demand and user profile

- High vehicle uptime enabling a continuous utilisation of vehicles, including low refuelling times
- Short but multiple driving distances due to inner-city traffic and deliveries, frequent stop-and-go

Deployment requirements

- Network of refuelling stations along relevant delivery routes or at least at key depots
- High safety standards for fuel cell components

Key other aspects

- Hybrid use of fuel cell as range extension for battery powered EV vs. fuel FCH drive train
- 200 km vehicle range will meet 97% of delivery van driving distances

Benefit potential for regions and cities

Environmental

- Zero tailpipe emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2)
- Low noise pollution (depending on speed and track conditions almost no noise emissions at all)

Social

- Public health benefits (esp. in urban areas), overall higher standard of living
- Lower adverse impact on residents adjacent to major inner-city logistics routes, e.g. retail pedestrian areas

Economic

- Development of expertise in FCEV technology as potential driver of future economic growth
- Reduction of dependency on fossil fuels or energy imports
- Increased attraction for region or city due to FCH infrastructure

Other

- Option to upgrade of existing battery-powered EV with fuel cell range extension
- Potentially high public, every-day visibility as "urban" FCH use case
- Potential to address last mile delivery in rural areas with long range requirements between refuelling cycles

Source: Roland Berger

Although first deployments are ongoing, further demonstration projects and additional vehicles are needed

Fuel cell electric vehicles – Delivery vans

4/4

Hot topics / critical issues / key challenges:

> **(Commercial) vehicle availability**, currently limited to range-extended battery electric vehicles and limited flexibility for vehicle selection

> **Current deployment** – further development of FCH delivery van prototypes and successful demonstration projects needed (still mainly in US, Europe needs to follow)

> **Range extension**, enlargement of operation range or further development of hybrid operation with battery powered powertrain for extension

> **Hydrogen infrastructure**, i.e. distribution logistics, local storage, refuelling stations and respective costs

> **Well-to-Wheel emissions**, reduction potential largely depends on resources used for hydrogen production

Further recommended reading:

> Official website of Hydrogen Mobility Europe: http://h2me.eu/

> Presentation on fuel cell hybrid electric delivery van project: https://www.hydrogen.energy.gov/pdfs/review16/tv034_hanlin_2016_o.pdf

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

FCH on garbage trucks today typically power loaders, compactors & range extension systems on diesel or EV[1] undercarriages

Fuel cell garbage trucks

1/4

Brief description: Fuel cell garbage trucks use compressed hydrogen and fuel cells to power the electric engine that empties garbage bins and compresses waste. Currently, only fuel cell range extended electric trucks or diesel trucks with power-box exist

Use cases: Cities and regions can use/promote fuel cell electric garbage trucks for waste collection; cities and regions can stipulate zero-emission vehicles through tender requirements

Fuel cell garbage trucks	FCH range extender	FCH power-box
Key components	Fuel cell stack and system module, hydrogen tank, battery, electric engine	"Power-box" for loader and compactor (truck power-train typically conventional diesel combustion)
Output	40 kW (extender)	32-68 kW (power box)
Range (full truck)	360 km (45-50kg H_2 tank)	200 km
Fuel	Electricity, hydrogen	Diesel, hydrogen
Consumption	6-9 kg H_2/100 km	*tbc*
OEMs & vehicle integrators	E-Trucks Europe, FAUN Kirchhoff, ULEMCo, Navistar, Heliocentrics	
Fuel cell suppliers	Hydrogenics, Symbio Fcell, Nedstack	
Typical customers	Offices of municipal sanitation, city cleaning companies	
Competing technologies	Battery electric, diesel combustion	

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1) Electric Vehicle

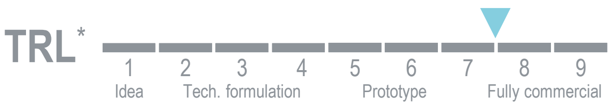
Source: Roland Berger

Currently, battery-FCH range-extended prototypes and diesel-hydrogen hybrid prototypes are part of demonstration projects

Fuel cell garbage trucks

2/4

Overall technological readiness: So far, only electric trucks with hydrogen fuel cell range extender or conventional diesel combustion powertrain with hydrogen fuel cell power-box for loader and compactor as prototype demonstration; no technology concept for entire fuel cell garbage truck publicly disclosed



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Levenmouth Community Energy Project Hydrogen Dual-Fuel garbage trucks[1)]	🇬🇧	2016	2 prototypes based on Heil Farid trucks in cooperation with ULEMCo converted to run on diesel power trains and hydrogen power box; project partners: Bright Green Hydrogen and Toshiba	n.a.
LIFE'N GRAB HY! (managed by European Commission (DB Environment and DG Climate Action))	🇳🇱 🇪🇺	2016	Phase 1: demonstration of two 26t hydrogen-electric hybrid garbage trucks by Cure Afvalbeheer (Eindhoven) and Baetsen Groep (Veldhoven) Phase 2: large-scale demonstration on 10 locations in Europe, planned for Sept. 2017	EUR 2.7 m
Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie (NIP)	🇩🇪	2011 - 2013	2-year test of world's first garbage truck with hydrogen fuel cell at Berliner Stadtreinigung (BSR). A diesel motor moves the vehicle and is turned off when it is loaded; the fuel cell powers the loader and compactor. Prototype built by FAUN Group, fuel cell from Heliocentris Energiesysteme GmbH	n.a.

1) Out of up to 25 vehicles of the project only 2 are garbage trucks

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Fuel cell garbage trucks have strong local FCH potential, especially regarding noise and NO_x / CO_2 emission reduction

Fuel cell garbage trucks

3/4

Use case characteristics

Stakeholders involved

- Users (municipality-owned & private waste management companies)
- Public authorities (vehicle approval, regulatory framework of pollutants etc.)
- OEMs, FC and Power-Box manufacturers
- H_2 suppliers and infrastructure providers

Demand and user profile

- High vehicle uptime enabling a continuous utilisation of vehicles, including low refuelling times
- Short but multiple driving distances due to inner-city traffic and decentralised waste collection
- Fast and powerful onboard waste management systems

Deployment requirements

- Network of refuelling stations along relevant routes or at least at key depots
- High safety standards for fuel cell components

Key other aspects

- Engine only produces low excess heat, additional heating of the driver's cabin necessary

Benefit potential for regions and cities

Environmental

- Reduction of CO_2 emissions and No_x pollutant emissions, improving air quality
- Reduction of noise emissions (still, some noise emissions at breaking, emptying and compressing)

Social

- Public health benefits (esp. urban areas near deployment route), reduced social security expenses, higher standard of living
- Lower adverse impact on residents adjacent to major inner-city routes

Economic

- Reduction of fuel consumption during waste collection of up to 30% (as stated by the Berlin waste management company, BSR)
- Energy savings and extension of brake durability through storage of breaking energy

Other

- Fast and smooth acceleration
- Potentially very visible FCH application for public demo purposes

Source: Roland Berger

Fuel cells already form part of demonstrational garbage truck fleets, with additional technological & commercial developments required

Fuel cell garbage trucks

4/4

Hot topics / critical issues / key challenges:

> **Current lack of availability of fully-fledged FCH applications**, only hybrid systems presented so far

> **Niche application**, due to low number of garbage trucks required by regions and cities there is no imminent economies of scale for regions and cities fit-for-purpose modularisation

> **Hydrogen infrastructure deployment**, i.e. expensive distribution logistics, local storage, refuelling stations and respective costs

> **Well-to-wheel emissions**, uncertain reduction potential largely depends on resources used for hydrogen production

> **Long-term procurement and services contracts**, e.g. concessions with private waste companies, limiting the scope of direct action for local public authorities

Further recommended reading:

> Life 'N Grab H4 project, technical explanation: http://www.lifeandgrabhy.eu/garbage-trucks-hydrogen

> Hydrogen Region for Flanders and the southern Netherlands: http://www.waterstofnet.eu/en/hydrogen-waste-collection-vehicle

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Hybrid and fully hydrogen-powered sweepers are a viable, efficient, zero emission and low-noise option for municipal services

Fuel cell sweepers

1/4

Brief description: FCH sweepers use fuel cells to power propulsion as well as brushes and vacuum cleaner; hybrid models where the fuel cell only drives the brushes/suction unit are also being pursued

Use cases: regions and cities can use fuel cell sweepers for cleaning streets as well as warehouses; regions and cities can promote zero-emission fuel cell sweepers e.g. through respective tender requirements

Fuel cell sweepers[1]	
Key components	Fuel cell stack and system module, hydrogen tank, battery, electric motor (for propulsion and brushes/suction unit)
Output	~30 kW (electric hydraulic drivetr.), 12 kWh lith.-ion battery
Range	1.5 days operating time (~one refuelling per day)
Fuel	Compressed hydrogen (350 bar)
Approximate capital cost	n.a.
Original equipment manufacturers and integrators	Bucher Municipal, Stock Sweepers, Global Environmental Products, Holthausen, Empa, Visedo
Fuel cell suppliers	Nedstack, Hydrogenics, US Hybrid
Typical customers	Offices of municipal sanitation, city cleaning companies
Competing technologies	Battery electric vehicles, diesel-combustion vehicles

[1] Example based on fully hydrogen powered Bucher CityCat H_2 as well as a Holthausen model converted in cooperation with Visedo

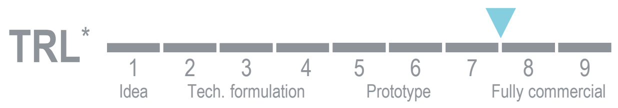
Source: Roland Berger

After successful demonstration deployment of prototypes, first pre-commercial orders show the TRL progress of FCH sweepers

Fuel cell sweepers

2/4

Overall technological readiness: advanced prototype/demo stage; several prototypes have been deployed in demonstration projects, including fully hydrogen powered sweepers; first commercial orders by California Department of Transportation (Caltrans) in May 2017



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Fuel cell sweeper demonstration with municipality of Groningen	🇳🇱	2017	Conversion of Holthausen diesel model into fuel cell electric sweeper in cooperation with municipality of Groningen, Netherlands and system integrator Visedo from Finland. Single hydrogen charge allows for 1.5 days of operation and noise pollution was reduced by half	n.a.
LIFE + ZeroHytechpark Project Street Yet Washer	🇪🇸	2014	Aragon Hydrogen Foundation developed and deployed a fuel cell sweeper. Project funded by the EU's LIFE programme	n.a.
hy.muve CityCat 2020 H_2	🇨🇭	2009	Test of CityCat H_2 , a hydrogen-powered street sweeper in the cities of Basel, St. Gallen and Bern. From August 2016 to August 2018 the sweeper is in use in the city of Duebendorf, Switzerland. Project partners: Bucher Municipal, research institutes EMPA and the Paul Scherrer Institute (hy.move consortium)	n.a.

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
Fuel Cell Electric Street Sweeper	GEP	80-Kilowatt FCe80 fuel cell, 200 kW driveline. The street sweepers are manufactured in San Bernardino CA by GEP, the electric powertrain and the fuel cell is manufactured by US Hybrid in Torrance CA and in South Windsor, CA	🇺🇸	2017	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Their deployment promises environmental benefits through emission reduction and higher utilisation due to lower noise

Fuel cell sweepers

3/4

Use case characteristics

Stakeholders involved	> Users (municipality-owned & private cleaning companies, warehouse operators) > Public authorities > OEMs, FC and Power-Box manufacturers > H_2 suppliers and infrastructure providers
Demand and user profile	> High vehicle uptime enabling a continuous utilisation of vehicles, including low refuelling times > Low noise pollution for indoor use like in exhibition halls and railway stations
Deployment requirements	> Hydrogen storage and refuelling infrastructure along relevant routes or at base stations/depots > High safety standards for fuel cell components
Key other aspects	> Engine only produces low excess heat, additional heating of the driver's cabin necessary

Benefit potential for regions and cities

Environmental	> Reduction of CO_2 emissions and No_x pollutant emissions, improving air quality > Reduction of noise emissions (still, some noise emissions at breaking, emptying and compressing), also dependent on speed & road quality
Social	> Public health benefits (esp. urban areas near deployment route), higher standard of living > Lower adverse impact on residents adjacent to major inner-city routes
Economic	> Reduction of power consumption by 50 to 70% compared to diesel, potentially lower TCO once CAPEX comes down > Low noise emissions, therefore possibility to clean at night times leading to higher utilisation of vehicles
Other	> Potentially very visible FCH application for public demo purposes

Source: Roland Berger

Infrastructure deployment & low standardisation due to niche app. & specific requirements, partially inhibit fully commercial deployment

Fuel cell sweepers

4/4

Hot topics / critical issues / key challenges:

> **Niche application**, due to relatively low number of sweepers required by regions and cities, economies of scale for regions and cities have to come from synergies with other FCH applications

> **Lack of standardisation**, induced by individual fit-for-purpose modularisation, hinders large scale production and additional economies of scale

> **Current deployment**, roll-out of fuel cell sweepers prototypes as demonstration projects; first commercial orders, as in the US, need to proceed

> **Hydrogen infrastructure deployment**, i.e. expensive distribution logistics, local storage, refuelling stations and respective costs

> **Well-to-Wheel emissions**, reduction largely depends on resources used for hydrogen production

Further recommended reading:

> Project description hy.muve:http://juser.fz-juelich.de/record/135720/files/TA1_pp_Schl_Schlienger_rev0604.pdf

> Project description Hoogezand: http://www.telegraph.co.uk/cars/news/clean-sweep-dutch-town-gets-hydrogen-fuel-cell-street-cleaner/

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

FCH construction equipment offers zero emission and low noise polluting opportunities, e.g. for inner-city civil works and O&M

Fuel cell construction mobile equipment & tractors

1/4

Brief description: Fuel cell construction mobile equipments such as tractors or excavators typically use fuel cells as a range extender for batteries (hybrid concept) or to fuel the complete machine including drivetrain and auxiliary systems

Use cases: Cities and regions can use/promote fuel cell electric construction machinery for building public infrastructure such as roads and paths, water and sewage networks, district heating networks, digital networks, as well as for the construction of public buildings

Fuel cell construction mobile equipment[1]

Key components	Fuel cell stack and system module, hydrogen tank, batteries, 2 electric motors (power to traction, power to PTO and auxiliaries)
Output	75 kW
Fuel	Hydrogen (diesel at hybrid models)
Reduction of noise	-10 dB (out-) /-20 dB (inside) compared to diesel peers
Approximate capital cost	n.a.
Original equipment manufacturers	Volvo, Hyundai, New Holland
Fuel cell suppliers	Symbio FCell, Hyundai
Typical customers	Building and road construction companies, farmers
Competing technologies	Diesel powered & battery powered drivetrains

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[1] Specifications mainly based on the New Holland NH2 tractor prototype

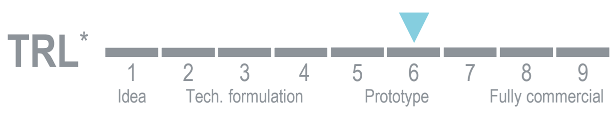
Source: Roland Berger

So far, only limited but advanced prototype demo projects for construction mobile equipment and tractors in Europe, mostly in SE

Fuel cell construction mobile equipment & tractors

2/4

Overall technological readiness: So far, systems are in the prototype stage undergoing trials in real-life environment (demonstration projects); no wide-spread deployment of commercially available products so far



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Elexc	🇸🇪	2015	Proof of concept of an electric excavator that combines battery and fuel cell system used as a range extender. Fuel cell from Symbio. Other partners: Volvo, Elbi, EFS, Prollion, Bonfigliolo, Ampère, ViaMéca, Tenerrdis.	n.a.
HF (Hyundai Future) Excavator	🇰🇷	2013	Design study of Hyundai in cooperation with design house tangerine of a crawler that can transform its shape and can be used in any terrain. Special design for rock fracture	n.a.
SFINX Crawler Excavator	🇸🇪	2009	Radically altered excavator concept from Volvo. Use of a fuel cell frees up space in the superstructure and allows engine to perform as "active counterweight"	n.a.
NH2™	🇮🇹	2008	Prototype based in a T6000 tractor of New Holland. Has undergone practical trials of New Holland's Energy Independent Farm concept "La Bellotta" in Venaria (Turin), Italy. Project consortium: New Holland, Elasis, Envi-Park, ENEA, CNR, Verderone, Tonutti, API-COM, CRF, Ferrari Costruzioni Meccaniche, Roter Italia, Sapio and Zefiro. Total project budget: EUR 11m, of which EUR 500.000 for tractor. Fuel cell: Nuvera; Part of Industria 2015 program "New technologies for Made in Italy", sponsored by the Italian Ministry for Economic Development	EUR 0.5 m

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Besides CO_2 and No_x emissions, FCH construction equipment reduces noise exposure – facilitating inner-city deployment

Fuel cell construction mobile equipment & tractors

3/4

Use case characteristics

Stakeholders involved	> Municipality-owned as well as private construction companies involved in construction of roads and paths, water and sewage networks, district heating networks, digital networks, as well as for the construction of public buildings > Farmers
Demand and user profile	> Operational in buildings or tunnels or densely populated areas > 24/7 operation possible due to fast recharging > Operation in challenging terrain necessary
Deployment requirements	> Refuelling infrastructure within reach of construction site –suitable for inner city areas. Otherwise decentralised / mobile supply and refuelling of hydrogen necessary
Key other aspects	> Engines only produce very few excess heat, therefore in some environments additional heating of the diver's cabin necessary

Benefit potential for regions and cities

Environmental	> No hazardous emissions, e.g. diesel leaks > No direct CO_2 or NO_x emissions > Quiet in use, ideal for busy public areas like pedestrian zones > Less hazardous waste compared to batteries
Social	> Health benefits for employees due to lower emissions and noise exposures > Public health benefits due to lower adverse impact on residents adjacent to major inner-city construction sites
Economic	> Completely redesigned machines, e.g. eliminating hydraulics lead to lower maintenance cost in the medium- to long-term > Low noise emissions, therefore possibility to work in the night leading to higher utilisation of vehicles
Other	> -

Source: Roland Berger

Limited deployments so far narrow empirical evidence of use case, but additional demonstration projects might mitigate bottleneck

Fuel cell construction mobile equipment & tractors

4/4

Hot topics / critical issues / key challenges:

- **Hydrogen infrastructure deployment**, i.e. expensive distribution logistics, local storage, refuelling stations and respective costs
- **Limited deployments**, low number of (demonstration) vehicles deployed so far, reducing empirical knowledge about usability of application
- **Well-to-wheel emissions**, uncertain reduction potential largely depends on resources used for hydrogen production
- **Long-term procurement and services contracts**, e.g. concessions with private construction companies, limiting the scope of direct action for local public authorities
- **Lack of standardisation**, induced by individual fit-for-purpose modularisation, hinders large scale production and additional economies of scale for regions and cities

Further recommended reading:

- Additional information regarding the Volvo prototype: http://www.symbiofcell.com/elexcpoc/
- Additional information regarding tractor prototypes: New Holland Tractor

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Material handling equipment comprises a large variety of systems, we focus on FCH-relevant applications (as currently anticipated)

Material-handling equipment – simplified overview

1 Transport equipment

- > Conveyors
- > Cranes
- > Pallet jacks
- > **Forklift trucks**1)
- > Narrow-aisle
- > Turret trucks
- > Order pickers
- > …

2 Positioning equipment

- > Lift/tilt/turn tables
- > Hoists
- > Balancers
- > Manipulators
- > Industrial robots
- > …

3 Unit load formation equ.

- > Pallets
- > Skids
- > Slipsheets
- > Tote pans
- > Bins/basket
- > Cartons, bags
- > Crates
- > …

4 Storage equipment

- > Bin shelving
- > Storage drawers
- > Carousels
- > A-frames
- > Racks
- > …

⬜ Potentially hydrogen fuelled applications 🟦 Exemplary application selected for technology introduction

1) Forklifts were selected due to their relatively advanced technological readiness and respective commercial diffusion of 10,000+ units in operation or in order globally

Source: Roland Berger

Fuel cell powered material-handling equipment offers multiple, purpose specific deployment options with a variety of benefits

Fuel cell powered material-handling equipment – e.g. forklifts

1/4

Brief description: Fuel cell material-handling equipment, e.g. forklift trucks, use compressed hydrogen gas as a fuel to generate electric power via an energy converter (fuel cell); the produced electricity powers an electric motor as well as the forklift

Use cases: multiple uses cases, incl. material handling at warehouses, recycling plants, construction sites, public work sites and municipal utilities; regions and cities can promote zero-emission vehicles through specific tender requirements e.g. forklifts

Fuel cell powered material handling

Key components	Fuel cell stack and system module, hydrogen tank, battery, electric motor
Output[1)]	2.5-4.5 kW
Fuel	Hydrogen (350 bar)
Refuelling interval; charging time[1)]	8 hours; 1-3 minutes
Weight; measurements of FC stack[1)]	270 kg; 624 x 294 x 627 mm
OEMs & system integrators	Linde, CAT, Hyster-Yale, Still, Fronius
Fuel cell suppliers	Ballard, Nuvera, PlugPower, Fronius
Typical customers	Logistics companies, warehouses, manufacturing facilities
Competing technologies	Battery electric vehicles, diesel engine vehicles or LPG

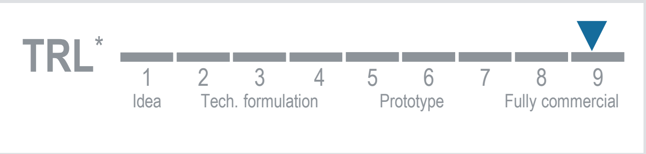
1) Based on 3 kW PEM Fuel Cell-Powered Pallet Truck according to US D.O.E. 2011
2) PlugPower GenDrive Series 3000
Source: Roland Berger

Material-handling equipment is a mature and widespread FCH application – both module-based and all-in-one solutions available

Fuel cell powered material-handling equipment – e.g. forklifts

2/4

Overall technological readiness: Commercial; currently > 10,000 fuel cell-powered forklifts are in operation or in order globally; already proven functionality through thorough long-term usage in real live environments



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Carrefour – Distribution center near Vendin-lès-Béthune (project part of HyLIFT-Europe)	🇪🇺	2016	150 class-2 & 3 electric lift trucks (STILL) powered with GenDrive (PlugPower) fuel cell stack units for a new distribution center	n.a.
E-LOG Biofleet at DB Schenker cross-docking terminal Hörsching, Austria	🇦🇹	2010 -2016	Test of battery-powered vehicles versus fuel cell-powered vehicles with 10 (+2) Linde T20-24 AP/SP stand-on pallet trucks operating 24/5	n.a.
BMW Manufacturing Co. LLC plant in Spartanburg, South Carolina.	🇺🇸	2010	~600,000 m^2 production plant operates more than 350 forklifts to service production and logistic functions; fleet reached > 1,000,000 fills (2015); energy reduction of 4.1 million kW/h p.a.	n.a.

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
T 20 pallet truck	Linde	Provides indoor truck solutions under the use of PlugPowers GenDrive technology	🇩🇪	2010	n.a.
Nuvera	Hyster-Yale	Fuel cell systems for electric lift trucks; PowerTap as supply equipment as well as PowerEdge as replacement for batteries	🇺🇸	2009	n.a.
GenDrive Series 1000, 2000 and 3000	PlugPower	24V, 36V and 48V FC modules for a broad range of vehicles like sit-down trucks, man-up order pickers, reach trucks, counterbalanced trucks, rider pallet jacks	🇺🇸	2008	n.a.

Source: Roland Berger

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Benefits include potentially increased utilisation, as well as lower emissions & noise pollution, esp. relevant within warehouses

Fuel cell powered material-handling equipment – e.g. forklifts

3/4

Use case characteristics

Stakeholders involved

- Users (warehouse & logistics operators, municipality-owned & private construction companies)
- OEMs, FC and Power-Box manufacturers
- H_2 suppliers and infrastructure providers

Demand and user profile

- Indoor & outdoor use
- Deployment in low & high temperature environments
- High productivity or throughput requirements
- Continuous operation
- High availability e.g. through fast charging & reliability,

Deployment requirements

- Hydrogen supply and local storage
- On-site hydrogen refuelling station
- Possibility of on-site fuel production from PV or wind

Key other aspects

- Due to technology conversion costs, greenfield deployment projects provide better ROI than fleet conversions within existing deployments, e.g. warehouses

Benefit potential for regions and cities

Environmental

- Reduction of CO_2 emissions and No_x pollutant emissions, improving air quality, esp. within warehouses
- Reduction of noise emissions, also dependent on speed & road quality

Social

- Health benefits for employees due to lower emissions and noise exposures

Economic

- Advantages vs. battery EV: refuelling <3 min vs. 8-10 hrs battery charging, +30% operating range; less space demand (battery charging room, charging docks); longer lifetime
- Potentially lower maintenance and repair cost compared to diesel engines – hence potential TCO1)-advantages

Other

- Compact in size, concentrated mass
- No voltage drop as seen in batteries and better performance at low temperatures compared to batteries

---

1) Total Cost of Ownership

Source: Roland Berger

System costs and tailored solutions drive costs and profitability, while emission reduction is determined by hydrogen production

Fuel cell powered material-handling equipment – e.g. forklifts

4/4

Hot topics / critical issues / key challenges:

> **Lack of standardisation**, induced by individual fit-for-purpose modularisation and a large variety of vendors, hindering large scale production and additional economies of scale

> **Strong competitive technologies,** being battery powered material handling equipment as well as diesel-backed systems

> **High CAPEX and system costs,** meaning a full scale deployment of FCH handling equipment requires distribution logistics, local storage, equipment and refuelling stations, among others. This in turn requires large numbers of deployed units in order to be run profitable

> **Well-to-Wheel emissions,** reduction potential largely depends on resources used for hydrogen production

Further recommended reading:

> U.S. Department of Energy (2014): Early Markets: Fuel Cells for Material Handling Equipment https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/early_markets_mhe_fact_sheet.pdf

> National Renewable Energy Laboratory publications on material handling: http://www.nrel.gov/hydrogen/publications.html

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

FC bikes offer almost 2.5 times the operating range of traditional e-bikes – Refuelling time only 2-6 minutes instead of up to 8 hours

Fuel cell electric bikes

1/4

Brief description: Fuel cell electric bikes use compressed hydrogen gas as a fuel to generate electricity via an energy converter (fuel cell) assisting the rider's pedal power through an electric motor

Use cases: Cities and regions can use/promote fuel cell electric bikes for bike sharing offerings and inner city services (e.g. police patrolling, deliveries, courier services, individual mobility of municipal staff, etc.) and integrate concept into local tourism strategy

Fuel cell electric bicycles	
Key components	Fuel cell stacks, hydrogen tank, electric motor
Output	0.1 – 0.25 kW
Top speed; range	25-35 km/h; >100 km
Fuel	Hydrogen (storage at 200-350 bar)
Fuel cell efficiency	~50%
Weight	23.6 kg (Linde H_2 Bike) – 34.6 kg (Gernweit bike)
OEMs & system integrators	Gernweit, Linde, Clean Air Mobility, Pragma Industries, Atawey (infrastructure)
Fuel cell suppliers	Linde, Pragma industries
Typical customers	Private costumers, postal/delivery services, bike sharing services
Competing technologies	Battery powered e-bikes, conventional bikes and scooters

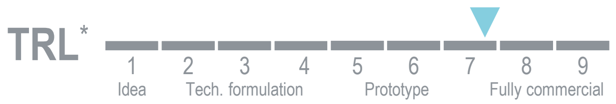
Source: Roland Berger

Fuel cell electric bikes are generally still in the (advanced) prototype phase and preparing for first demonstration projects

Fuel cell electric bikes

2/4

Overall technological readiness: Fuel cell electric bikes are generally still in the advanced prototype phase and first demonstration projects and larger field tests and first commercial projects are ongoing (esp. in FR)



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Gernweit "Ped-Hy-lec"	🇩🇪	2008	Prototype development with two separate tanks to refuel has started in 2008 in cooperation with the ministry for innovation, science and research of the state of North Rhine-Westphalia	n.a.
HyChain Minitrans	🇪🇺	2006	Development of low power fuel cell vehicle fleet to initiate an early market for hydrogen applications that are optimised in design and functionality	n.a.
UNSW Hy-Cycle	🇦🇺	n.a.	First Australian fuel cell powered pedelec developed by UNSW researchers allowing range of up to 125 km and a maximum speed of 35 km/h	n.a.

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
H_2-Bike	Linde	Pre-commercial demonstrational prototype series of fuel cell powered pedelec bike based on "Cannondale Contro E"-chassis, pedal support for up to 100 km	🇩🇪	2017	~4.000€
Alpha	Pragma Industries	Small scale production and testing of fuel cell powered pedelec bikes using modified FC systems from Toyota including a Li-Ion battery as bridging energy, market introduction of two models planned for 2017	🇫🇷	2016	~6.500€

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

FC bikes can be environmentally advantageous compared to battery-powered bikes, especially when fuelled with green hydrogen

Fuel cell electric bikes

3/4

Use case characteristics

Stakeholders involved

- Bike-sharing operators, bike rental providers – especially in tourism applications
- Postal and other delivery services
- Municipal service providers
- OEMs, infrastructure providers

Demand and user profile

- Touristic areas with good cycling infrastructure, touristic bike rental services
- Potentially especially mountainous or otherwise challenging terrain – driving support for longer range and uphill terrain

Deployment requirements

- Hydrogen refuelling infrastructure, incl. production, distribution, storage and refuelling stations
- Compliance with local road traffic regulation and associated certifications

Key other aspects

- Reliable theft protection required due to high investment cost
- Superior operability at low temperatures compared to battery powered bikes

Benefit potential for regions and cities

Environmental

- Compared to battery powered bikes, significant environmental advantages due to avoidance of ecologically harmful disposal of batteries
- Zero-emission potential with "green" hydrogen

Social

- n/a

Economic

- Longer lifetime compared to battery-powered bikes
- Potentially lower OPEX and hence Total Cost of Ownership advantage vis-à-vis battery-powerd bikes (once investment costs have come down)

Other

- Extended operating range and better fit with certain long-range use cases (e.g. deliveries, couriers, tourism), short refuelling time
- No self-discharge as it is the case with conventional batteries

Source: Roland Berger

Technology readiness of FCH scooters has to be improved – use cases and associated value propositions need to be further refined

Fuel cell electric bikes

4/4

Hot topics / critical issues / key challenges:

> **Refinement of use cases** and **value proposition**, i.e. focus on bike sharing, touristic or other bike rental services, delivery services, etc.

> **Hydrogen infrastructure** , location and coverage of hydrogen refuelling stations; high cost for hydrogen and its distribution/storage as hurdle for overall commercial attractiveness

> **Technological readiness,** most models still in prototype phase; models of Linde, Atawey and Pragma Industries in (pre-) commercial stage

> **Environmental sustainability,** with well-to-wheel emissions largely dependent on resources used in hydrogen production

Further recommended reading:

> Linde H_2 bike booklet: http://www.linde-gas.com/internet.global.lindegas.global/en/images/19279_H2_bike_handbook_English17_176415.pdf

> Hychain Minitrans Project Overview: http://www.ap2h2.pt/download.php?id=19

> Pragma H_2 bike booklet: http://www.pragma-industries.com/company/press-releases/alter-bike/

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

FCH electric scooters offer a viable option for emission free and low noise mobility, especially within densely populated inner-city areas

Fuel cell electric scooters

1/4

Brief description: Fuel cell electric scooters use compressed hydrogen gas as a fuel to generate electricity via an energy converter (fuel cell) to power an electric motor

Use cases: Cities and regions can use/promote fuel cell electric scooters for inner city services (e.g. police patrolling, postal services, deliveries, individual mobility of staff, etc.); cities and regions can establish "environmental zones" (zero-/low-emission-zones) to promote deployment

Fuel cell electric scooters1)	
Key components	Fuel cell stacks, hydrogen tank, electric motor
Output	3-4 kW
Top speed; range	50-70 km/h; up to 350 km (at constant 30 km/h)
Consumption	~0.23kg H_2/h (at rated power of 3.9 kW)
Fuel cell efficiency	~53% (at rated power of 3.9 kW)
Approximate capital cost	EUR 3,100 (APFCT)
Original equipment manufacturers	APFCT, Suzuki
Fuel cell suppliers	APFCT, Suzuki, Intelligent Energy Holding
Typical customers	Private consumers, public and private inner city services
Competing technologies	Battery EV, gasoline- or CNG-combustion

1) Mainly based on the FCH model offered by APFCT and the Suzuki Burgman

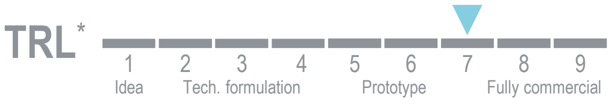
Source: Roland Berger

One FCH electric scooter already in pre-commercial stage, another model in advanced prototype demonstration phase

Fuel cell electric scooters

2/4

Overall technological readiness: Fuel cell electric scooters are still in prototype phase; hybrid set-up combining battery power source with fuel cells are common; High price and lack of refuelling infrastructure as main obstacle for widespread market introduction.



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Hydrogen scooter testing and verification program		2010	Phase 1: Evaluation of 30 APFCT fuel cell powered scooters in road tests conducted by Taiwan Institute of Economic Research (TIER) Phase 2: One year verification project by offering 80 APFCT fuel cell powered scooters to public, analysis and monitoring via GPS data	n.a.
HyChain Mini-Trans	🇪🇺	2006 - 2011	Development of FC vehicle fleet in four regions in Europe (DE, E, FR, IT) to generate enough market volume for applications, e.g. fuel cell scooters	EUR 37.7 m (total project)
HySy Rider by HySyLab	🇮🇹	2005 - 2008	FC expertise network; Development of fuel cell powered scooter (HySy Rider) as part of viability study in Piedmont region;	n.a.
European Development of a Fuel-Cell Reduced-Emission Scooter (FRESCO)	🇪🇺	2001 - 2005	Make FC suitable for scooters & improve viability by developing a modern mass production-type scooter	EUR 3.6 m

Products / systems available (selection)

Name	OEM		Product features	Country	Since	Cost
Burgman	Suzuki		Pre-commercial version on public roads in Japan and UK; First fuel cell scooter to earn European Whole Vehicle Type Approval (WVTA)	🇯🇵	2010	n.a.

Source: Roland Berger

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Zero tailpipe emissions and low noise pollution improve standard of living, especially in inner-city, densely populated areas

Fuel cell electric scooters

3/4

Use case characteristics

Stakeholders involved

- OEMs, fuel cell suppliers, hydrogen suppliers
- Public and private city service providers (e.g. police force, postal / delivery services, local / regional authorities, etc.)
- Private or fleet customers (e.g. rental companies)

Demand and user profile

- Range, performance and refuelling process similar to conventional scooters

Deployment requirements

- Hydrogen refuelling infrastructure, incl. production, distribution, storage and refuelling stations
- Compliance with local road traffic regulation and associated certifications

Key other aspects

- For some use cases (e.g. Loughborough Met Police) back-to-base refuel strategy to avoid necessity of currently not established refuelling infrastructure

Benefit potential for regions and cities

Environmental

- Zero tailpipe emissions
- Low noise pollution (depending on speed and road surface, close to zero)
- Potential substitution of larger, stronger polluting vehicles like cumbustion engine powered cars

Social

- Public health benefits (esp. urban areas) on residents adjacent to major inner-city routes

Economic

- Longer lifetime compared to battery modules
- Lower OPEX compared to battery powered scooter sharing operations

Other

- Extended operating range and lower refuelling time

Source: Roland Berger

Premium price and refuelling infrastructure as well as further technical development to be addressed as critical issues

Fuel cell electric scooters

4/4

Hot topics / critical issues / key challenges:

> **Premium price**, high premiums to be paid by customers buying fuel cell electric scooters, especially in Europe

> **Space limitation**, due to established scooter designs, lack of space for accommodating fuel cell system, including tanks

> **Refinement of use cases and value proposition**, i.e. focus on scooter sharing, touristic or other scooter rental services, delivery services, etc.

> **Hydrogen infrastructure**, location and coverage of hydrogen refuelling stations; high cost for hydrogen and its distribution/storage as hurdle for overall commercial attractiveness

> **Technological readiness,** most models still in prototype phase; Suzukis Bergman in (pre-) commercial stage

> **Environmental sustainability**, well-to-wheel emissions largely depend on resources used in hydrogen production

Further recommended reading:

> Suzuki fuel cell scooter overview: http://www.intelligent-energy.com/uploads/Suzuki_case_study.pdf

> Hychain Minitrans Project Overview: http://www.ap2h2.pt/download.php?id=19

> FRESCO information sheet: https://ec.europa.eu/research/energy/pdf/efchp_fuelcell18.pdf

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

C. WG3: "Maritime and aviation transport applications"

Working Group 3 deals with six FCH applications in the maritime and aviation fields

Working Group 3: Maritime and aviation transport applications

1. Ferries
2. Boats
3. Ships
4. Port operations equipment
5. Aircraft
6. Airport ground operations

30 regions & cities are part of the Working Group 3 from **14** European countries

17 industry participants are now part of Working Group 3 from **9** European countries

BOC
Air Liquide
H2B2
Maritim Forening
ariema
HYSEAS ENERGY
CALVERA Hydrogen
PersEE Innovation
ITM POWER
BALLARD
NAVAL GROUP
PM PROTON MOTOR
cEnergy
AURIGA energy
HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD
FERGUSON marine
SEMA consulting

Source: Roland Berger

FC powered boats could significantly reduce emissions and noise pollution in recreational areas as well as densely populated regions

Fuel cell powered boats

1/4

Brief description: Fuel cell boats (< 500 tons) use compressed hydrogen gas as a fuel to generate electric power via an energy converter (fuel cell); the produced electricity powers an electric motor; **technical specifications are highly dependent on specific recreational or public transport use cases**

Use cases: Cities and regions can use/promote fuel cell boats for emergency service units, water taxis as well as tourist sightseeing and boat rentals; Cities and regions can establish harbours as "environmental zones"

Fuel cell powered boats1) (typically use-case specific)

Key components	Fuel cell stack, system module, hydrogen tank, battery, electric motor
Output; efficiency	4 kW; up to 47% efficiency
Fuel	Hydrogen (350 bar)
Speed	5 kts
Refuelling interval; time of charging	80 km, < 5 min
Approx. capital cost	EUR 148,000 (excl. VAT)
Original equipment manufacturers	Frauscher, Bitter, Cheetah Marine
Fuel cell suppliers	Fronius, ITM Power, PowerCell Sweden AB, Proton Motor Fuel Cell, Hydrogenics , YC Synergy
Typical customers	Emergency units, water taxi and boat rental operators
Competing technologies	Diesel, battery-electric motors

1) Based on one example of Frauscher 600 Riviera HP

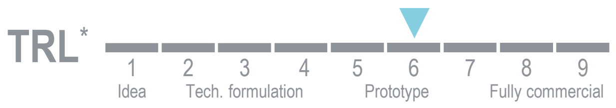
Source: Roland Berger

Various worldwide prototype demonstrations in operational environment since the early 2000s

Fuel cell powered boats

2/4

Overall technological readiness: Advanced prototype stage, albeit very diverse product segment with man different types of boats for a range of different recreational and public transport use cases; demonstration projects in operational environment have been completed or are currently ongoing



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Energy Observer	🇫🇷	2015	Lightweight ex-racing catamaran (30.5m length) using wind and solar power with on-board electrolysis to fuel a fuel cell. Round-the-world trip started in July	EUR 5 m
Ship as part of the Island Hydrogen (formerly known as EcoIsland)	🇬🇧	2012	9.95 m fuel cell catamaran, completed 100 km around the Isle of Wight in 8 hours, average speed 7-8 kts (top speed 12 kts). Project funded by "Innovate UK"	n.a.
Future Project Hydrogen	🇦🇹	2009	6 m boat "Frauscher 600 Riviera HP" powered by a 4 kW hydrogen fuel cell, funded by the state of Upper Austria	n.a.
Zero CO2	🇫🇷	2009	CEA Liten zero CO2 12m hybrid electric sailboat with 30 kW PEM Fuel cell system and 15 kWh Li-ion battery	n.a.
Xperiance NX hydrogen	🇳🇱	2006	12 person boat with a 1.2 kW PEM fuel cell propulsion system; designed to travel 2-3 days without refuelling, funded by the Province of Friesland and the Dutch Ministry of Economic Affairs	n.a.
Duffy-Herreshoff DH 30 Watertaxi	🇺🇸	2003	30-day demonstration of a fuel cell/battery electric water taxi for up to 18 passengers and 4x 1.5 kW PEM fuel cell; partially funded by California's Center for the Commercial Deployment of Transportation Technologies (CCDoTT)	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Low emission powertrain and low noise pollution bears significant benefit potential for regions and cities

Fuel cell powered boats

3/4

Use case characteristics

Stakeholders involved	> Emergency organisations (police, fire service, rescue organizations) > Municipalities and/or private operators offering water taxis and boat trips > OEMs
Demand and user profile	> Sensitive ecologic environments requiring alternative (zero emission, low noise pollution) propulsion systems > Peak demand in high seasons (need for fast refuelling)
Deployment requirements	> Refuelling infrastructure > High safety standards for hydrogen storage and transportation > Possibility of coupling with on-site electrolysis from solar or wind
Key other aspects	> Currently only single demonstration boats; no entire fuel cell fleet in operation

Benefit potential for regions and cities

Environmental	> Zero local emissions (CO_2, pollutants, fine dust particles) > Reduced noise level, therefore suitable in sensitive environments > Potential to reduce environmental risk of accidents
Social	> Increased public acceptance of boat services, especially in harbour cities (zero emissions) > Ultimately thanks to low/zero emission footprint: higher standard of living in critical areas
Economic	> Depending on the development of oil prices, CAPEX reduction and cost of hydrogen – lower TCO in the long run than diesel-fuelled boats
Other	> Refuelling time of a few minutes vs. battery charging of 8-10 hours

Source: Roland Berger

Product cost and hydrogen refuelling infrastructure as most critical issues for implementation on a larger scale

Fuel cell powered boats

4/4

Hot topics / critical issues / key challenges:

> **Identification** of suitable use cases and customers/users

> **Hydrogen infrastructure** (storing and refuelling stations in harbours, challenging logistics of providing the infrastructure for remote areas)

> **Product cost** (reducing the cost of fuel cells and batteries; cost competitiveness with electric boats has not been achieved yet; economies of scale hard to achieve as boats mostly are very individualized products)

> **Lack of overall industry standardization, certification guidelines and regulation** (esp. for refuelling protocols, hydrogen dispensing, bunkering, etc.)

> **Technological readiness** (until now, only prototype demonstration projects in operation; esp. emergency services or water taxi operators require fast and agile boats)

> **Eco-friendliness** (well-to-wheel emissions largely depend on resources used in hydrogen production)

Further recommended reading:

> EMSA Study on the use of fuel cells in shipping, 2017 http://www.emsa.europa.eu/news-a-press-centre/external-news/download/4545/2921/23.html

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Currently pursued FCH hybrid ships are a lower emission and lower noise alternative to diesel, esp. for inner-city harbours

Fuel cell powered ships

1/4

Brief description: Fuel cell ships use compressed hydrogen as a fuel to generate electric power via an energy converter (fuel cell); the produced electricity powers an electric engine; ***current concepts and prototypes mainly focus on auxiliary power supply for seagoing vessels***

Use cases: Cities and regions can use/promote fuel cell ships to reduce emissions and fuel use. Authorities and port operators can establish harbours as "environmental zones" and require other forms of electricity generation/supply in the harbours than from the fossil fuel engine of the ships

Fuel cell powered ships (typically use-case specific, e.g. depending on route serviced)

Key components	Fuel cell stack and system module, hydrogen tank, battery, electric motor
Fuel cell technology	Proton exchange membrane (PEM), solid oxide (SOFC)
Output[1]	50 – 500 kW
Fuel	Hydrogen, LNG, methanol, diesel
Approximate capital costs	n.a.
Original equipment manufacturers	Wartsilä Ship Design, Fincantieri, ABB
Fuel cell suppliers	Nuvera, PowerCell Sweden AB, Proton Motor Fuel Cell, Serenergy , FuelCell Energy (FCES)
Typical customers	Offshore companies, research organizations, logistics providers, tour operators
Competing technologies	Diesel, methane, LNG

1) Auxiliary power based on Project SchIBZ

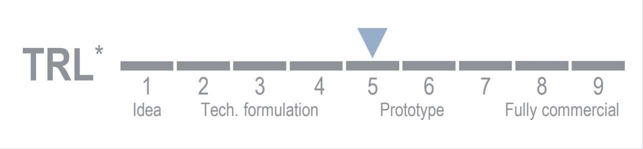
Source: Roland Berger

Prototypes and demonstration projects mainly focus on auxiliary power supply – FCH propulsion applications still under development

Fuel cell powered ships

2/4

Overall technological readiness: Auxiliary power units for large scale ships and small- to medium-scale ships in prototype and demonstration phase (projects to field-test in relevant environments are now under way), fuel cell propulsion application still in early concept phase



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
MARANDA	🇪🇺	2017	165 kW (2 x 82.5 kW AC) fuel cell powertrain (hybridized with battery) for power to research vessel's electrical equipment, dynamic positioning during measurements. Partners: Powercell, ABB, OMB Saleri, PersEE, SYKE, Swiss Hydrogen	EUR 3.7 m
Orion® fuel cell stack prototype units test at Fincantieri	🇮🇹	2013	Fincantieri and Nuvera agreed to build ships with Orion ® fuel cell stacks used as range extenders on marine vessels	n.a.
SMARTH2 project Elding	🇮🇸	2007	125-ton cruiser previously used as rescue ship and retrofitted to be used for whale watching tours with up to 150 passengers. Hybrid 10 kW fuel cell system replaced a 50 kW diesel engine for auxiliary power	n.a.
e4ships	🇩🇪	2009	Association of leading German dockyard and ship operators working on joint industry projects to significantly improve energy supply onboard large vessels using (high-temp.) PEM and SOFC as well as CHP. Funded under the National Innovation Program Hydrogen and Fuel Cell Technology (NIP)	EUR 35 m
FellowSHIP project Viking Lady Offshore Supply Vessel	🇳🇴	2003	DNV 1A1 Supply Vessel, 2009 delivered to Eidesvik Offshore, chartered to Total, power requirements covered by LNG fuelled molten carbonate fuel cell	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

FC powered ships could significantly decrease environmental impacts of maritime traffic (emissions, oil & diesel spills, noise)

Fuel cell powered ships

3/4

Use case characteristics

Stakeholders involved	> Shipping companies (public & private) > Shipowners > Research organizations > Port authorities > OEMs and fuel cell technology providers
Demand and user profile	> Shipping routes and use cases with sensitive ecologic environments requiring alternative propulsion systems > Shipping routes and use cases with harbours where main engines are turned off to minimize noise, vibration and air pollution
Deployment requirements	> Hydrogen refuelling infrastructure (at harbours, possibility of coupling with electrolysis from renewable resources like solar or wind) > High safety standards for hydrogen storage and transportation
Key other aspects	> Currently no demonstration of large ship solely powered by hydrogen fuel cells, focus on auxiliary systems (in addition to diesel engines)

Benefit potential for regions and cities

Environmental	> Local zero-emission performance whenever fuel cell auxiliary systems are in use > Reduced noise level, therefore suitable in sensitive (urban or rural) environments > Potential to reduce environmental risk of accidents
Social	> Increased public acceptance of boat services, especially in harbour cities (no harmful emissions) > Ultimately thanks to low/zero emission footprint: higher standard of living in critical areas
Economic	> Eventually reduced cost in harbours, esp. in countries with high electricity prices where vessels have to rely on external electricity supply when in harbour > Depending on the development of oil prices, CAPEX reduction and cost of hydrogen – lower TCO in the long run
Other	> Hydrogen infrastructure at berths can be used both for port operations and docked ships

Source: Roland Berger

Technological readiness as well as technical standards and hydrogen infrastructure as key challenges

Fuel cell powered ships

4/4

Hot topics / critical issues / key challenges:

> **Technological readiness** (for now, no entirely fuel cell powered ship available; evolution to the next development stage necessary going beyond auxiliary power supply)

> **Regulation** (lacking of consistent European as well as world wide regulation regarding the permission to use gaseous hydrogen in harbours)

> **Technical standards** (derivation of technical standards for different types of ships varying concerning systems and performance)

> **Hydrogen infrastructure** (storing and refuelling stations in harbours, challenging logistics of providing the infrastructure for remote areas)

> **Eco-friendliness** (well-to-wheel emissions largely depend on resources used in hydrogen production)

> **System Integratio**n (Efficient use of battery and fuel cell energy)

> **Product cost** (reducing the cost of fuel cells and batteries)

Further recommended reading:

> EMSA study on the use of fuel cells in shipping: www.emsa.europa.eu/emsa-documents/latest/download/4545/2921/23.html

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

FC powered ferries offer a zero emission and low noise polluting alternative especially for short distance connections

Fuel cell powered ferries

1/4

Brief description: Fuel cell ferries use compressed hydrogen gas as a fuel to generate electric power via an energy converter (fuel cell); the produced electricity powers an electric motor

Use cases: Cities and regions can use/promote fuel cell ferries as alternative to heavy-oil ferries to connect remote areas as well as to establish connections within a city or region. Authorities and port operators (region- or municipality-owned) can establish harbors as "environmental zones"

Fuel cell powered ferries (typically use-case specific, i.e. depending on route serviced)

Key components	Fuel cell stack and system module, hydrogen tank, battery, electric motor
Output	12 kW – 2.5 MW
Fuel	Hydrogen (stored at 350 bar)
Speed	6 - 35 knots
Passenger capacity	12 - 150
Approximate capital cost	EUR 255,000[1)]
Original equipment manufacturers	*TBC*
Fuel cell suppliers	Auriga energy, Ballard Power Systems, Proton Motor
Typical customers	Logistics operators, water taxi operators, ship owners
Competing technologies	Diesel, LNG

1) Based on Hydrogenesis (Bristol)

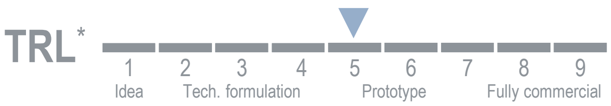
Source: Roland Berger

So far, only small ferries are in prototype demonstration – Larger ferry applications still in concept phase

Fuel cell powered ferries

2/4

Overall technological readiness: Application overall at prototype stage, to be demonstrated in relevant environment over the coming months and years



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
HYBRIDShips	🇳🇴	2017	Pilot model of a hybrid-powered ferry, which will be in operation in 2020. Main propulsion based on H_2 fuel cells, To ensure energy-efficient operation, batteries will also be used. Project partners: Fiskerstrand Holding AS, Norwegian Maritime Authority (NMA)	n.a.
MF Ole Bull	🇳🇴	2016	Demonstration project at Osterøy car ferry between Valestrand and Breinstein. One of the ferry's two diesel engines will be replaced by an electric motor powered by a 200 kW PEM fuel cell. Project partners: Christian Michelsen Research Prototech (CMR) GreenStat	n.a.
HYSEAS III	🇬🇧	2016	As continuation of Hyseas 2 project , Hyseas III aims to take the concept of a hydrogen powered passenger and vehicle ferry through to a construction project. HYSEAS III consortium managed by Fergusson Marine Engineering Limited: Fergusson Marine (shipbuilder), Caledonian Assets Management ltd. (ship owner/Scottish Government owned), Kongsberg Maritime (R&D), St. Andrews University, Ballard Power Systems, Transport Scotland (associate)	n.a.
Hydrogen Ferry Demonstration Project in Bristol "Hydrogeneisis“	🇬🇧	2010-2014 & since 2016	6-month trial with a 11 m steel ferry in Bristol. Powered by four 12 kW fuel cells, the ferry carries 12 passengers and two crew. The hydrogen fuel and refueling station for the ferry are supplied by Air Products.	EUR 255,000.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

FC powered ferries could dramatically decrease environmental impacts of ferry services (emissions, oil & diesel spill, noise)

Fuel cell powered ferries

3/4

Use case characteristics

Stakeholders involved

- Municipality-owned and/or private transport companies operating water taxis and car ferries
- Ship owners
- Port authorities
- OEM & utility providers

Demand and user profile

- Sensitive ecologic environments requiring alternative (zero emission, low noise pollution) propulsion systems
- Peak demand in high seasons (need for fast charging and intensive use)

Deployment requirements

- Refueling infrastructure
- High safety standards for hydrogen storage and transportation
- Possibility of coupling with electrolysis at harbor from renewable resources like solar or wind

Key other aspects

- Significant reduction of dependency on fossil fuels or energy imports (depending on the type of hydrogen production)

Benefit potential for regions and cities

Environmental

- Zero local emissions (pollutants, CO_2)
- Reduced noise level, therefore suitable in sensitive environments, such as rivers, lakes and oceans
- Beneficial to the wild life of rivers, lakes and oceans

Social

- Increased public acceptance of boat services (no harmful or disruptive emissions)
- Ultimately thanks to low/zero emission footprint: lower health insurance expenses, reduced social security expenses and higher standard of living

Economic

- Eventually reduced cost in harbors of countries with high electricity prices where vessels are not allowed to use diesel for electricity production and instead have to rely on external electricity
- Depending on the development of oil prices, lower TCO in the long run

Other

- The University of the Highlands and Islands, Orkney College, elaborated a concept for a Hydrogen Vessel Training to familiarize ship crews with fuel cells. A 75 kW fuel cell is used to mimic the fuel cell on a vessel

Source: Roland Berger

Technological readiness and regulatory limits as well as the provision of a hydrogen infrastructure are among the key challenges

Fuel cell powered ferries

4/4

Hot topics / critical issues / key challenges:

> **Technological readiness** (systems still in proof-of-concept phase and not yet commercially available). For now, only prototype demonstrations for smaller passenger ferries. However, several car ferry demonstration projects are in the planning stage and will start to operate by the year 2020

> **Hydrogen infrastructure** (storing and refueling stations in harbors, challenging logistics of providing the infrastructure for remote areas)

> **Eco-Friendliness** (well-to-wheel emission largely depends on resources used in hydrogen production)

> **Product cost** (cost reduction of fuel cells and batteries)

> **Regulation** (unresolved regulatory issues such as certification of the equipment; emergency protocols; permitting of hydrogen use)

Further recommended reading:

> EMSA study on the use of fuel cells in shipping: www.emsa.europa.eu/emsa-documents/latest/download/4545/2921/23.html

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

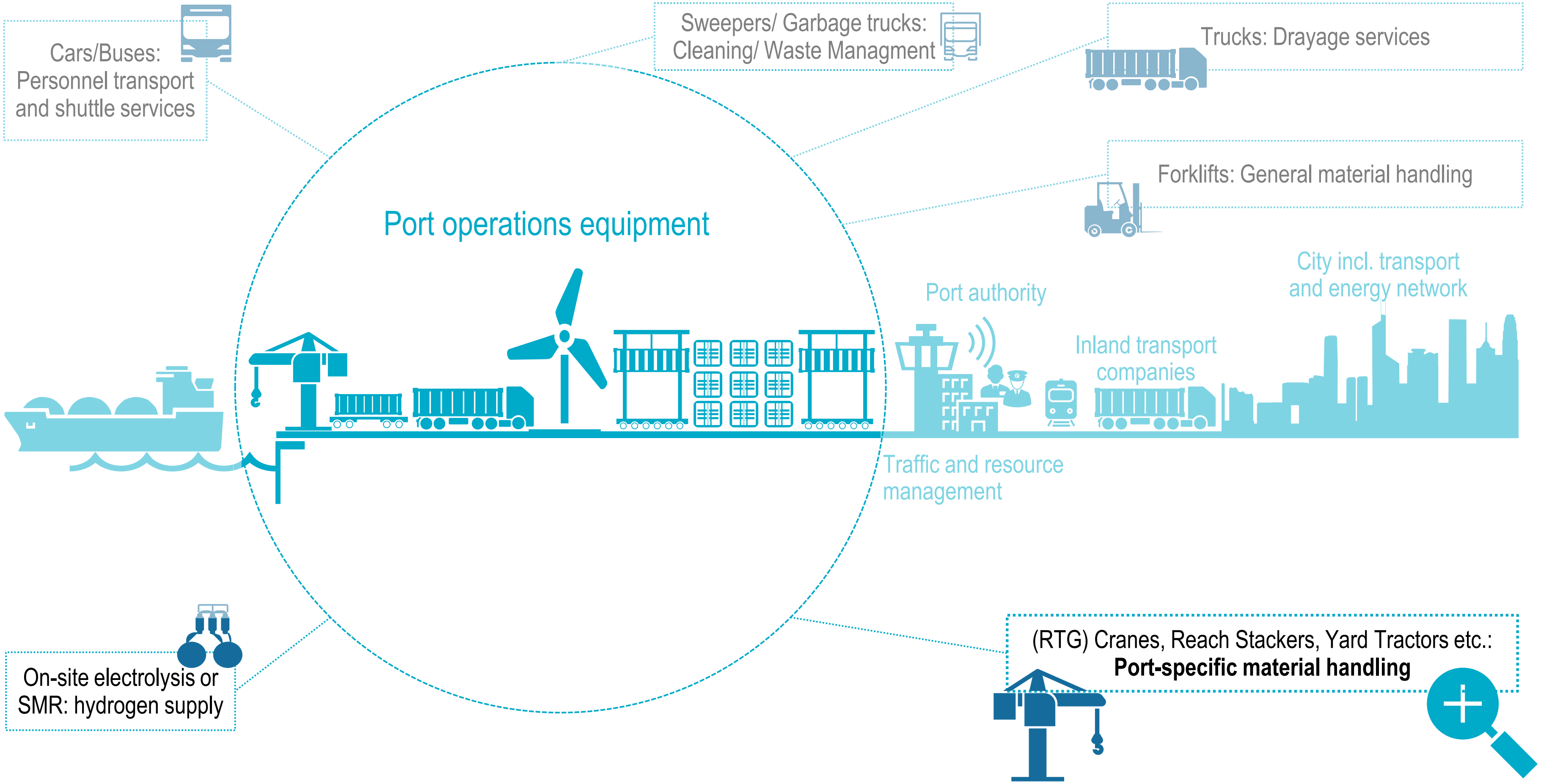
https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Port operations require numerous types of equipment – some applications have been already covered in other Working Groups

Fuel cell powered port operations equipment (selection)

1/5



Cars/Buses: Personnel transport and shuttle services

Sweepers/ Garbage trucks: Cleaning/ Waste Managment

Trucks: Drayage services

Forklifts: General material handling

Port operations equipment

On-site electrolysis or SMR: hydrogen supply

(RTG) Cranes, Reach Stackers, Yard Tractors etc.: **Port-specific material handling**

Source: Roland Berger

Port operations equipment today is offered on a diesel, (battery) electric or hybrid basis - FCH appl. not yet commercially available

Fuel cell powered port operations equipment (selection)

2/5

	RTG Cranes A	**Reach Stackers** B	**Yard Tractors** C
			
Brief description	Rubber tyred gantry (RTG) cranes are mobile cranes which are used to ground or stack containers from yard tractors or drayage trucks and vice versa	Reach Stackers are used to handle containers and other cargo in ports; they are both able to shortly transport as well as to pile containers	Yard tractors are used to transport trailer and containers short distances from ships to distribution centres or container terminals and vice versa
OEMs	Liebherr, Kalmar, Konecranes, Sany	Liebherr, Kalmar, Konecranes, Sany, Hyster-Yale, Terex	Terberg, Kalmar, Orange EV
Engine	Diesel, electric (via a conductor bar for example), hybrid (diesel/electric)	Diesel, hybrid (diesel/electric)	Diesel, (battery) electric, hybrid (diesel/electric)

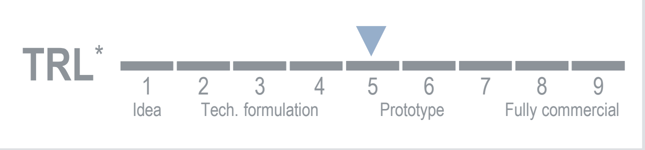
Source: Roland Berger

Various port operators tackle emission reduction goals via demos of FCH equipment – so far mainly with non-port-specific applications

Fuel cell powered port operations equipment

3/5

Overall technological readiness: Application overall at prototype or even still concept stage, to be demonstrated in relevant environment over the coming months and years; however some equipment (e.g. forklifts) more advanced than other



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Project Portal	🇺🇸	2017	Proof of concept with a Toyota heavy-duty truck for drayage operations at the Ports of Los Angeles and Long Beach. The truck fuel cell system, powered by two Mirai fuel cell stacks and a 12kWh battery, is capable of supporting port drayage operations. It will operate to support class 8 load operations, generating more than 670 horsepower and 1,800 Nm torque, with an estimated driving range of about 320 km per fill	n.a.
Surf ´n´ Turf	🇬🇧	2016	Surplus generated by onshore wind on the Orkney Islands is converted into hydrogen by a 500 kW electrolyser and shipped to the port of Kirkwall where – among others – a fuel cell is used to supply electricity to ships while docked	n.a.
Demo2013	🇫🇮	2011	Vuosaari Harbour at the Port of Helsinki demonstrates FC applications in a variety of port applications (stationary FCs as well as FCs for material handling equipment) e.g. Wärtsilä 50kW SOFC, Hydrocell portable FC, metal hydride storage for boats, H_2 refuelling station by Woikoski Oy. Project partners: Federation of Finnish Technology Industries and the Port of Helsinki	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Significant decrease of emissions and very low noise pollution as major benefits – especially for inner-city harbours

Fuel cell powered port operations equipment

4/5

Use case characteristics

Stakeholders involved

- Municipality-owned and/or private port operaters and logistics companies
- Port authorities
- OEMs

Demand and user profile

- 24/7 operation requiring fast refuelling time
- Range, performance and refuelling service offerings ideally similar to conventional port operations equipment, in order that no operational changes are needed

Deployment requirements

- Hydrogen storage and refuelling infrastructure
- High safety standards for hydrogen storage and transportation

Key other aspects

- Possibility of coupling with on-site electrolysis from solar or wind

Benefit potential for regions and cities

Environmental

- Zero local emissions (CO_2, pollutants, fine dust particles)
- Depending on the production type of hydrogen, down to zero well-to-wheel emissions
- Significantly reduced noise level, therefore especially beneficial to inner-city harbours

Social

- Increased public acceptance of commercial harbours, especially in cities
- Ultimately thanks to low/zero emission footprint and low noise pollution: higher standard of living in areas near the harbour
- Improved working conditions for harbour workers

Economic

- Depending on the development of oil prices, CAPEX reduction and cost of hydrogen – lower TCO in the long run than diesel-fuelled port operations equipment
- As ports comprise an entire ecosystem, it is easier to generate a critical mass of hydrogen vehicles and applications for efficient and cost-effective hydrogen supply

Other

- Depending on the production type of hydrogen, reduction of dependency on fossil fuels or energy imports

Source: Roland Berger

Ports have to offer demo cases, industry has to define products and develop prototypes for port-specific FCH applications

Fuel cell powered port operations equipment

5/5

Hot topics / critical issues / key challenges:

- **Technological readiness and system/product definition** (until now, only proof of concepts and prototype demonstration projects in operation – and hardly any for port-specific applications e.g. in port-specific material handling; very specific operational requirements regarding the various potential use cases of fuel cells for port operation equipment)
- **Product cost** (capital expenditures expected to be significantly higher than for equipment powered by diesel; business case highly dependent on fuel prices with port operators requiring a positive return on investment)
- **Hydrogen infrastructure** (availability of distribution logistics, local storage and refuelling stations must be ensured; adequate location inside or outside the harbour must be found)
- **Environmental sustainability** (well-to-wheel emissions largely depend on resources used in hydrogen production)
- **Regulation** (unresolved regulatory issues such as certification of the equipment; emergency protocols; permitting of hydrogen use)
- **Training of workers** (usage as well as storage of hydrogen; behaviour in case of emergencies)

Further recommended reading:

- Fuel Cells 2000: Port of the Future
  www.hfcarchive.org/fuelcells/uploads/Port-of-the-Future.pdf
- FCH2 JU 2017 Workshop on Maritime and port applications
  http://www.fch.europa.eu/event/workshop-maritime-and-port-applications

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Current research and development focuses on small-scale airplanes (< 5 passengers) and auxiliary power for conventional aircraft

Fuel cell powered aircrafts

1/4

Brief description: Fuel cell powered aircraft use compressed hydrogen gas as a fuel to generate electric power via a fuel cell for propulsion or auxiliary power; ***current concepts and prototypes mainly focus on non-essential aircraft applications for conventional aircraft***

Use cases: Cities and regions can use/promote fuel cell aircraft to reduce carbon emissions and noise pollution

Fuel cell powered aircraft [1)]

Key components	Fuel cell stack and system module, hydrogen tank, battery, electric motor
Output	80 kW
Fuel	Hydrogen
Top speed, range	200 km/h, 750-1500 km
Battery capacity	21 kWh
Approximate capital costs	n.a.
Original equipment manufacturers	Boeing, Airbus, Lange Aviation, Pipistrel
Fuel cell suppliers	Hydrogenics, NuCellSys
Typical customers	Airline operators
Competing technologies	Battery powered and conventional aircraft (kerosene)

1) Based on "HY4" project by DLR

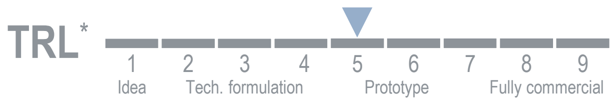
Source: Roland Berger

Until now, only small-scaled aircraft with fuel cell powertrain in prototype stage as well as testing of auxiliary power units

Fuel cell powered aircrafts

2/4

Overall technological readiness: Experiments and early prototyping of fuel cell technology as auxiliary power unit (APU) on large conventional aircraft or as propeller powertrain for smaller aircraft



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Demonstration of "HY4"-aircraft	🇩🇪	2016	Demonstration of world's first 4 seat passenger aircraft powered by fuel cell technology, operation by DLR spinoff H2FLY with future vision of "electric air taxi network"	n.a.
Hydrogen Cells for Airborne Usage (HYCARUS)	🇪🇺	2013	European research project led by Zodiac Aerospace to develop a Generic Fuel Cell System (GFCS) in order to power non-essential aircraft applications; objective is to establish alternative sources to power non-propulsive aircraft systems, funded by FCH2 JU with EUR 5,2 m	EUR 12 m
DLR, Airbus and Michelin fuel cell testing	🇩🇪	2008	Testing of various fuel cell application on A320 e.g. fuel cell powered electric nose wheel to significantly reduce noise and emission levels at airports when moving/taxiing on the runway	n.a.
Project Hydrogenius	🇪🇺	2008	Cooperation of University of Stuttgart (Germany) and Slovenian small aircraft OEM Pipistrel to construct fuel cell powered two-seater aircraft	n.a.
Environmentally Friendly Inter City Aircraft powered by Fuel Cells (ENFICA-FC)	🇪🇺	2006	Designing of a fuel cell powered manned intercity aircraft as part of aeronautics and space priority of the Sixth Framework Programme (FP6)	EUR 4.5 m

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Significant decrease of emissions and much lower noise pollution as major benefits – especially for airports in densely populated areas

Fuel cell powered aircrafts

3/4

Use case characteristics

Stakeholders involved

- Airline operators
- OEM & Fuel Cell Suppliers
- Airport operators
- Public regulators

Demand and user profile

- Range, performance and refuelling service offerings ideally similar to conventional aircraft, however not yet technologically ready

Deployment requirements

- Hydrogen refuelling infrastructure
- High safety standards for hydrogen storage and transportation

Key other aspects

- Short distance regional transport as potential entry scenario

Benefit potential for regions and cities

Environmental

- Zero local emissions as substantial advantage
- Significantly lower noise pollution than with using conventional aircraft

Social

- Higher standard of living in areas near airports which are significantly polluted by noise and emissions
- Improved public consent for aircraft
- Health benefits for workers and passengers through reduced noise and pollution

Economic

- Extended interval of engine maintenance due to less activity if nose wheel[1] or the auxiliary power unit (APU) is run by a fuel cell, which replaces the engine on ground
- Higher power efficiency for auxiliary power generation

Other

- Depending on the production type of hydrogen, reduction of dependency on fossil fuels or energy imports

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1) as tested by DLR, Airbus and Michelin since 2008

Source: Roland Berger

Technological readiness as well as product cost as major challenges for large-scale implementation of fuel cell powered aircraft

Fuel cell powered aircrafts

4/4

Hot topics / critical issues / key challenges:

- **Technological readiness and system/product definition** (until now, no entirely fuel cell powered commercial aircraft available and current propulsive applications limited to very small aircraft; evolution to the next development stage necessary going beyond prototyping for auxiliary power supply; very specific operational requirements regarding the various potential use cases of fuel cells in aircraft)
- **Product cost** (reducing the cost of fuel cells and batteries; significantly higher CAPEX than for conventional aircraft)
- **Technical standards** (derivation of technical standards for different types of aircraft varying concerning systems and performance)
- **Hydrogen infrastructure** (storing and refuelling stations in airports, challenging logistics of providing the infrastructure for remote areas)
- **Eco-friendliness** (well-to-wheel emissions largely depend on resources used in hydrogen production)

Further recommended reading:

- Official website of HY4: http://hy4.org/

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Aircraft ground support equipment constitutes an entire ecosystem with numerous potential use cases for fuel cell applications

Fuel cell powered aircraft ground support equipment (GSE)

1/4

Brief description: Fuel cell powered aircraft ground support equipment (GSE) use compressed hydrogen gas as a fuel to generate electric power via an energy converter (fuel cell); the produced electricity powers an electric motor; ***various GSE is in use at airports which constitutes an entire ecosystem – numerous potential use cases***

Use cases: Cities and regions can use/promote fuel cell aircraft ground support equipment to reduce emissions and noise pollution as well as health and working conditions for workers and travelers

Fuel cell powered ground support equipment (GSE) 1)

Key components	Fuel cell stack and system module, hydrogen tank, battery, electric motor
Output	20kW
Max. speed	25 km/h
Fuel	Compressed hydrogen (CGH2) at 350 bar
Refuelling interval, time of charging	8 hours, 3-4 min.
Approximate capital costs	n.a.
Original equipment manufacturers	Mulag Fahrzeugwerk, Charlatte
Fuel cell suppliers	H_2 Logic, Ballard Power Systems, Plug Power
Typical customers	Airport operators, logistics companies
Competing technologies	Diesel, LPG, CNG, battery electric

1) Based on towing tractor "Comet 3 FC" by Mulag

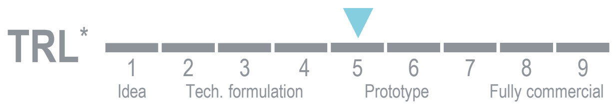
Source: Roland Berger

Until now, only few prototype demonstrations available – technology to be further tested to prove technological readiness

Fuel cell powered aircraft ground support equipment (GSE)

2/4

Overall technological readiness: Prototypes developed, demonstration projects in operational environment complete or ongoing (albeit mostly outside Europe)



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Department of Energy (DOE) ground support equipment demonstration	🇺🇸	2013	Phase 1: Development of fuel cell system for cargo tractor application Phase 2: Demonstration of 15 fuel cell powered cargo tractors in airport operation Partners: FedEx, Plug Power, Charlatte, Memphis-Shelby County International Airport	EUR 4.2 m
HyLIFT-DEMO and HyLIFT-EUROPE	🇪🇺	2012	Large scale demonstration of material handling/GSE with the participation of Mulag towing tractors with a Comet 3 FC prototype. Trials at Hamburg and Cologne/Bonn airports and performance testing at Mulag's premises in Oppenau, Germany	EUR 22.3 m1)
Department of Energy (DOE) Small Business Innovation Research Program	🇺🇸	2011	Department of Energy has selected InnovaTek to receive a Phase I award under its Small Business Innovation Research Program for development of a fuel cell range extender for battery-powered airport ground support equipment. InnovaTek will collaborate with EnerFuel, a fuel cell developer, and JBT AeroTech, a GSE manufacturer	EUR 130,000

1) Also includes other material handling equipment than towing tractors

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Significant environmental benefit potential – synergies between the various GSE could contribute to cost-effective hydrogen supply

Fuel cell powered aircraft ground support equipment (GSE)

3/4

Use case characteristics

Stakeholders involved
- Airport operators and specialized ground handling companies
- Airport authorities
- OEM s

Demand and user profile
- Range, performance and refueling service offerings ideally similar to conventional GSE
- 24/7 operations in 3 shifts

Deployment requirements
- Hydrogen storage and refuelling infrastructure
- High safety standards for hydrogen storage and transportation

Key other aspects
- Fuel cells automatically shut off when not needed, no idling required

Benefit potential for regions and cities

Environmental
- Zero carbon and greenhouse gas (GHG) emissions
- Low noise pollution
- Reducing overall environmental footprint of airports

Social
- Higher standard of living in areas near airports which are significantly polluted by noise and emissions
- Improved public consent for airport infrastructure
- Health benefits for workers and passengers through reduced noise and pollution

Economic
- Fuel Cells are twice as efficient as diesel engines
- No investment into electric infrastructure needed compared to battery electric fleets
- As airports comprise an entire ecosystem, it is easier to generate a critical mass of hydrogen vehicles and applications for efficient and cost-effective hydrogen supply

Other
- Depending on the production type of hydrogen, reduction of dependency on fossil fuels or energy imports

Source: Roland Berger

Technological readiness, product cost as well as hydrogen supply as critical issues to increase fuel cell applications in airports

Fuel cell powered aircraft ground support equipment (GSE)

4/4

Hot topics / critical issues / key challenges:

- **Technological readiness and system/product definition** (until now, only proof of concepts and prototype demonstration projects; very specific operational requirements regarding the various potential use cases of fuel cells for ground support equipment)
- **Product cost** (capital expenditures expected to be significantly higher than for equipment powered by diesel and other fuels; business case highly dependent on fuel prices with airport operators requiring a positive return on investment)
- **Hydrogen infrastructure** (availability of distribution logistics, local storage and refuelling stations must be ensured; adequate location inside or outside the airport must be found)
- **Environmental sustainability** (well-to-wheel emissions largely depend on resources used in hydrogen production)
- **Training of workers** (usage as well as storage of hydrogen; behaviour in case of emergencies)

Further recommended reading:

N/A

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

D. WG4: "Stationary applications"

Working Group 4 addresses seven types of stationary fuel cell applications (incl. some variants within)

Working Group 4: Stationary Applications

1. Resid. use / FC mCHP
2. Commercial buildings
3. Industrial use cases
4. Back-up power
5. Off-grid power
6. Gen-sets
7. *(District heating – please refer to industrial use cases)*
8. *(Biogas in fuel cells – please refer to industrial use cases)*

42 regions & cities are part of the Working Group 4 from **15** European countries

22 industry participants are now part of Working Group 4 from **8** European countries

BOC
AFC Energy
atawey
AREVA
CALVERA Hydrogen
AURIGA energy
fuelcellenergy
PLUG POWER EUROPE
H2B2
ariema
cEnergy
Ceres Power
VIESSMANN
eps
SOLID POWER
ITM POWER
HyET Hydrogen
HYDROGENICS
Logan Energy
sunfire
PM PROTON MOTOR
storengy

Low emissions and noise are among the key advantages of fuel cell powered gen-sets compared to conventional diesel systems

Fuel cell powered gen-sets

1/4

Brief description: Fuel cell powered gen-sets are transportable stationary fuel cells that use compressed hydrogen gas to generate electricity via an energy converter (the fuel cell) to provide electricity for a wide array of potential applications that temporarily require off-grid power supply

Use cases: Fuel cell powered gen-sets can replace diesel gen-sets in any context where transportable, controllable power generation is needed (e.g. construction sites) and hydrogen can be supplied – to help reduce carbon, pollutant and noise emissions; they could be promoted e.g. in civil works tenders

Fuel cell powered gen-sets	
Key components	Fuel cell stacks, system module, hydrogen tank, battery, inverter, transport vehicle
Fuel cell technology	Proton exchange membrane (PEM)
Fuel	Hydrogen
Electrical efficiency (net)	up to 50% FC, possibly higher in the future
Output	n.a.
Approximate capital cost	n.a.
Original equipment manufacturers	BOC, Young Brothers, Plug Power, EPS
Fuel cell suppliers	Ballard Power Systems, Hydrogenics, EPS
Typical customers	Telecom providers, hospitals, construction and maintenance services companies
Competing technologies	Combustion-engine diesel generators

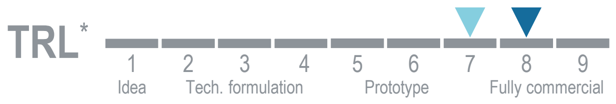
Source: Roland Berger

The wide field of application for mobile FC gen-sets ranges from construction sites to maritime on-board auxiliary power

Fuel cell powered gen-sets

2/4

Overall technological readiness: Fuel cell gen-sets systems are commercially available in a variety of sizes, power ranges and application possibilities in non-European markets, various use cases are in commercialisation phase; in Europe, the segment is in the advanced protoype/demo phase



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
EVERWH2ERE	🇪🇺	2017	FCH2 JU roject cooperates with two OEMs and a number of site operators including construction companies, festival organisers and some public authorities for the deployment (demonstration) of genset fuel cells	n.a.
Maritime Hydrogen Fuel Cell Project	🇺🇸	2012	Field demonstration of fuel cell powered gen-sets in commercial maritime port setting of Honolulu hosted by Young Brothers Ltd. and U.S. Department of Energy (DOE), objective is to replace diesel generators in providing auxiliary power on-board of ships and to ships at berth	n.a.
TOWERPOWER demonstration project	🇪🇺	2011	Development of low-cost fuel cell based power generator system called PowerCubeTM to replace diesel generators e.g. to power mobile communication towers	EUR 9.4 m

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
Ecolite-TH2	BOC	Low energy LED fuel cell powered lighting tower for construction/maintenance work, up to 750 hours runtime depending upon fuel cylinder configuration	🇬🇧	n.a.	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Besides noise and emissions reduction, fuel cell powered gen-sets reduce the risk of diesel spillage

Fuel cell powered gen-sets

3/4

Use case characteristics

Stakeholders involved	> Users: telecom providers, public institutions, construction and maintenance services > OEMs, fuel cells and hydrogen suppliers > Permitting and licensing authorities
Demand and user profile	> Flexible off-grid operations in need for temporary, off-grid and controllable power supply such as lighting for construction/ maintenance work, ships in port
Deployment requirements	> Hydrogen production and delivery services > Appropriate hydrogen storage infrastructure
Key other aspects	> Operation under all weather conditions as self-start in low temperatures possible > Operation in residential neighborhoods as well as underground possible

Benefit potential for regions and cities

Environmental	> Zero emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2) > Low noise pollution due to almost silent operation > No risk of diesel spillage
Social	> Higher safety and decreased exposure to harmful emissions e.g. for construction workers (compared to traditional diesel generators)
Economic	> Long-term cost saving potential compared to conventional diesel generators, provided that capital cost come down and hydrogen cost decrease further
Other	> Reduction of diesel consumption and stability of power supply

Source: Roland Berger

Cost-efficient fuel supply concepts have to be delivered – Economies of scale can help bring down costs

Fuel cell powered gen-sets

4/4

Hot topics / critical issues / key challenges:

> Cost-efficient fuel supply concepts for delivery of hydrogen to the site of usage

> High requirements regarding purity level of hydrogen needed for fueling PEM-based gen-sets

> Need for further product availability in Europe

> Further reduction of capital cost through economies of scale necessary for large scale implementation of gen-sets (as with other stationary fuel cell)

> Lack of component standardisation within value chain (similar for a number of stationary fuel cells)

> Limited EU-wide rules and standards for hydrogen storage and transport

Further recommended reading:

> TOWERPOWER project

> FITUP project

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Fuel cell mCHPs provide heat and electricity to residential and small commercial buildings, using natural gas and existing infrastructure

Fuel cells for residential and small commercial buildings (fuel cell micro-CHPs) 1/4

Brief description: fuel cell micro combined heat and power units (FC mCHPs) use natural gas as fuel to generate electricity and heat through a fuel cell stack reforming natural gas on site to hydrogen. Combined with an auxiliary boiler, they can replace entire residential heating systems or they can supply base-load electricity with add. heat supply

Use cases: Cities/regions can promote FC mCHPs in 1/2-family dwellings, SMEs or other residential / small commercial developments (e.g. in municipal housing developments, office complexes) to lower carbon emissions, improve efficiency and enable smart grids. Using natural gas, they build on existing fuel infrastructure

Fuel cell for residential use (ranges reflect industry portfolio, selection of companies)

Key components	Fuel cell stacks, system module, inverter, heat exchanger, auxiliary condensing boiler, combined storage tank
Fuel cell technologies	Proton Exchange Membrane (PEM), Solid Oxide (SOFC)
Fuel	Natural gas (generally also biogas or other methane)
Electrical / Combined efficiency	35-60% / 85-90% (PEM), 80-95% (SOFC)
Output	0.3-5 kW_{el} (PEM), 0.8-2.5 kW_{el} (SOFC)
Approximate capital cost	EUR 10,000-35,000[1]
Original equipment manufacturers	Viessmann, SolidPower, Elcore, Bosch, BDR Thermea
Fuel cell suppliers	SOLIDpower, Hexis, Panasonic, Elcore, Sunfire
Typical customers	Private home owners, municipal housing providers, residential real estate developers, utilities, SMEs
Competing technologies	Heating systems (e.g. gas boilers), power grid

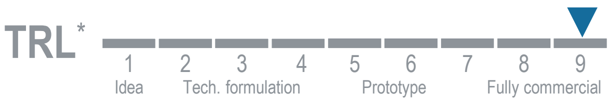
[1] Please refer to the next slide for three examples

Source: Roland Berger

Fuel cell mCHPs are one of the most mature FCH technologies with several European products commercially available

Fuel cells for residential and small commercial buildings (fuel cell micro-CHPs) 2/4

Overall technological readiness: Large scale field tests completed across Europe and esp. in Germany; fuel cell CHP systems of advanced generations from various OEMs now commercially available, other OEMs have announced to follow in the near term (EU catching up to East-Asian markets)



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
PACE	🇪🇺	2016	Horizon 2020 funded project to help European mCHP sector take the next step to mass market commercialisation with ~2,650 units by 4 mCHP OEMs	EUR 90 m
European wide field trials for residential fuel cell micro-CHP (ene.field)	🇪🇺	2011	Europe's largest demonstration project with ~1,000 residential fuel cell micro CHP installations across 11 countries to demonstrate market potential and push commercialisation	EUR 52 m
Callux field test	🇩🇪	2008	Field test of ~500 fuel cell powered heating units for residential use for a period of 7 years demonstrating commercial feasibility and long lifetime of application	EUR 75 m

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Approx. cost[1]
BlueGEN	SOLIDpower	1.5 kW_{el} / 0.6 kW_{th} SOFC mCHP with efficiency of up to 60%$_{el}$ and combined 85% for distributed base-load electricity supply with waste heat for warm-water supply	🇮🇹 🇩🇪	2012	EUR 10,000 – 25,000 (possibly add. installation cost), strongly dep. on local sourcing cond. and use case
Vitovalor 300-P	Viessmann	FC mCHP as full heating system (incl. aux. boiler) with 0.75 kW_{el} / 1kW_{th}, heat-driven operations, PEM FC from Panasonic with combined efficiency of up to 90%	🇩🇪	2014	
Elcore 2400	Elcore	305 W_{el} / 700 W_{th} PEM FC mCHP for base-load electricity supply with waste heat for warm-water supply with combined efficiency of up to 104% (incl. aux. boiler)	🇩🇪	2014	

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

1) Indicative range – not considering specific use case context, local sourcing conditions (esp. installation cost), subsidies

Source: Roland Berger, FCH2 JU, FC mCHP OEMs, Thermondo

Fuel cell mCHPs significantly reduce local emissions of CO_2 and pollutants while building on existing natural gas infrastructure

Fuel cells for residential and small commercial buildings (fuel cell micro-CHPs)

3/4

Use case characteristics

Stakeholders involved

- FC mCHP OEMs, FC technology providers
- Wholesalers and installers
- Utilities, gas and electricity grid DSOs
- Private consumers, real estate owners, SMEs

Demand and user profile

- Heat and electricity demand of 1/2 family dwellings or small commercial buildings
- 2 basic operating models: heat-driven FC mCHPs follow heat-load profile of building and produce electricity in the process, add-on mCHPs provide base load electricity with waste heat for warm water

Deployment requirements

- Connection to natural gas grid for fuel supply and electricity grid (for feed-in of surplus electricity)
- Typically availability of local installation, service and maintenance force

Key other aspects

- Emerging trend of partial self-sufficient energy supply in households / "self-reliance"

Benefit potential for regions and cities

Environmental

- Low emissions of pollutants and greenhouse gases (esp. CO_2) – reduction of 25-70% of CO_2 in representative German 1/2-family home, reduction of primary energy consumption
- Low noise pollution due to almost silent operation

Social

- Promotion of distributed energy systems, lowering social cost of electricity grid expansion esp. by DSOs (e.g. local combination of FC mCHPs and heat pumps)
- Enabler for more renewables in electricity mix with complementary role of distributed CHP to e.g. heat pumps

Economic

- With reduction of product cost due to volume uptake and learning effects, TCO-competitiveness with other high-end heating solutions in reach (esp. in near term thanks to subsidy programmes) – esp. in markets with high spark spreads for consumers (difference of gas and electricity prices)

Other

- Creation of micro-CHP networks throughout regions and communities to help balancing grid needs – smart grid potential

Source: Roland Berger

Pressure to reduce cost for a fully convincing economic value proposition is a key issue – as is business model innovation

Fuel cells for residential and small commercial buildings (fuel cell micro-CHPs) 4/4

Hot topics / critical issues / key challenges:

> Need to reduce high product cost and CAPEX for consumers (currently still higher capital and maintenance cost than for conventional heating units), obstacle in residential market (even as TCO-competitiveness with other premium systems comes within reach)

> Technical standardisation as lever for cost reduction (inhomogeneity of installation procedures in different countries posing barrier for market expansion)

> Sustaining and improving technical performance (esp. durability and system lifetime, but also electrical efficiency)

> Defining innovative business models, esp. financing solutions and sales channels ("go-to-market")

> Regulatory and policy-support circumstances (demand for FC mCHP systems currently supported by subsidies)

> Public acceptance (lack of public awareness or acceptance of fuel cell powered micro-CHP)

Further recommended reading:

> "Advancing Europe's energy systems: Stationary fuel cells in distributed generation": http://www.fch.europa.eu/studies

> “Business models and financing arrangements for the commercialisation of stationary applications of fuel cells report” (forthcoming): http://www.fch.europa.eu/studies

> http://enefield.eu/

> http://www.pace-energy.eu/

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Medium-size fuel cell CHPs can meet the growing demand for energy-efficient and independent solutions in commercial buildings

Fuel cells in commercial buildings (5-100 kW_{el} and up to 400 kW_{el})

1/4

Brief description: fuel cell combined heat and power systems (FC CHP) for commercial buildings use natural gas as fuel to generate electricity and heat through a fuel cell stack reforming natural gas on site to hydrogen – for distributed energy supply in office/public-sector buildings, buildings, hospitals, hotels, SMEs, etc.

Use cases: Cities and regions can promote fuel cells in commercial buildings to lower GHG and carbon emissions and increase resilience against unexpected power outages – particularly for commercial buildings such as small to medium size enterprises (SMEs) , hotels, hospitals, public sector buildings, etc.

Fuel cells in commercial buildings[1]

Key components	Fuel cell stacks, system module, inverter, heat transmission and storage
Fuel cell technology	likely mainly SOFC (possibly also PEM, MCFC, PAFC)
Fuel	Natural gas (possibly also biogas, hydrogen)
Efficiency	ca. $50\%_{el}$, ca. 85% combined
Output	5-100 kW_{el} (and up to 400 kW_{el})
Approximate capital cost	dep. on use case and market, ca. EUR 18,000-30,000 per kW_{el} (fully installed)[2]
OEMs, system integrators	TBD – e.g. Convion, Logan Energy, FuelCell Energy (FCES)
Fuel cell suppliers	FCES – e.g. Sunfire, mPower, elcogen, SOLIDpower, Ceres Power
Typical customers	Office building developers, public sectors, hotel/hospital operators
Competing technologies	Gas boiler & grid supplied electricity, conventional CHP

[1] Focus on European market

[2] Down to less than EUR 6,000 per KW_{el} if kW ~400)

Source: Roland Berger

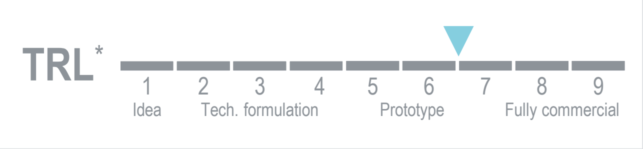
ComSos project potentially to be added

In Europe, fuel cells in commercial buildings are still at a comparatively early stage in tech. development and deployment

Fuel cells in commercial buildings (5-100 kW_{el} and up to 400 kW_{el})

2/4

Overall technological readiness: Limited range of products available in Europe that are mostly in advanced-prototype / demo-project stage (North American and East Asian markets are to some extent more mature), EU manufacturers however starting to develop products (prototype / demo or early commercial trial stage)



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
First commercial deployment in hotel	🇩🇪	2017	Installation of 400 kW fuel cell by FCES through e.on in Radisson hotel facility in Frankfurt. 3 GWh electricity production and 600 t of CO_2 reduction	n.a..
CHP fuel cell system in Fenchurch 20 Office Tower	🇬🇧	2014	Installation of 300 kW CHP fuel cell system running on natural gas to power major office tower in downtown London, reduction of carbon emission by 6-7% and awarded with BREEAM excellence rating	n.a.
MCFC deployment in Federal Ministry	🇩🇪	2013	Installation of 250 kW MCFC of FCES in office building of Federal Ministry in Berlin, Germany as innovative concept for combined supply of electricity, heat and chilling (incl. power supply for data centre)	n.a.
Fuel cell CHP industrial demonstration by US Department of Energy	🇺🇸	2010	Installation of 15 CHP fuel cell systems in small commercial buildings to document market viability through engineering, environmental and economic data analysis	n.a
PEM fuel cells in real conditions (EPACOp)	🇫🇷	2002	Assessment of performance of CHP fuel cell systems in public buildings (e.g. universities, city halls) and various testing conditions	EUR 2.4 m

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Fuel cell CHP systems can improve the overall energy efficiency of commercial buildings and significantly reduce overall emissions

Fuel cells in commercial buildings (5-100 kW_{el} and up to 400 kW_{el})

3/4

Use case characteristics

Stakeholders involved	> OEMs of CHP systems and FC suppliers > Planners, architects, installers > SMEs, commercial/public operators, facility managers > Utilities, ESCOs, power/gas grid operators
Demand and user profile	> Energy- and especially heat-intensive commercial buildings, e.g. hotels, hospitals, office buildings > Facilities with particular need for resilience against unexpected power outages, hence affinity for distributed energy supply
Deployment requirements	> Connection to existing gas/electricity grid > Sufficient space for distributed energy system, (semi-)central heat distribution system
Key other aspects	> -

Benefit potential for regions and cities

Environmental	> Low emissions of pollutants and greenhouse gases (esp. CO_2) – significant reduction CO_2, virtual elimination of NOx and SOx emissions, reduction of primary energy consumption > Low noise pollution due to almost silent operation
Social	> Promotion of distributed energy systems, lowering social cost of electricity grid expansion esp. by DSOs > Enabler for more renewables in electricity mix with complementary role of distributed CHP to e.g. heat pumps
Economic	> With reduction of product cost due to volume uptake and learning effects, TCO-competitiveness with other distributed energy solutions in reach – esp. in markets with high electricity prices for SMEs (difference of gas and electricity prices)
Other	> -

Source: Roland Berger

More fuel cell products are necessary in the commercial segment, most promising specific use cases need to be defined

Fuel cells in commercial buildings (5-100 kW_{el} and up to 400 kW_{el})

4/4

Hot topics / critical issues / key challenges:

- Lack of fuel cell products in this size range (currently, there are very few fuel cell CHP products which target the 2-100 kW_{el} size range, and the limited development to date has focused on the smaller end of the range e.g. 2-5 kW_{el})
- Competition with lower electricity and gas prices from grid supply – more challenging business case for distributed CHP compared to other segments
- Identification of most promising commercial use cases and corresponding operating models – distinct role of planners, engineers, architects, etc. as key influencers on FC definition and adoption
- Awareness of technological and commercial viability among policy makers

Further recommended reading:

- "Advancing Europe's energy systems: Stationary fuel cells in distributed generation" http://www.fch.europa.eu/studies
- "Business models and financing arrangements for the commercialisation of stationary applications of fuel cells report" (forthcoming) http://www.fch.europa.eu/studies

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Large-scale fuel cells in the industrial segment typically service specific use cases with efficient, low-emission distributed energy

Fuel cells in industrial and other large-scale stationary use cases

1/4

Brief description: Stationary fuel cell plants in industrial use cases typically generate power or combined heat and power (CHP) at MW-scale by converting natural gas, biogas or compressed hydrogen (from a grid or locally available), e.g. for electricity- (and heat-)intensive industrial production processes

Use cases: Cities and regions can use/promote fuel cells in industrial use cases to reduce CO_2 emissions, pollutant emissions and primary energy consumption. Typical use cases are energy-intensive industries (chemical, pharma, food & beverage), wastewater treatment facilities, data centres

Fuel cells in industrial use cases[1]

Key components	Fuel cell stacks, system module, inverter, heat exchange, storage
Fuel cell technology	AFC, MCFC, SOFC, PAFC, PEM
Fuel	Primarily natural gas, but also biogas and hydrogen (if on site)
Efficiency	~50%$_{el}$, combined >80%
Output	typically > 400 kW$_{el}$, up to multi-MW$_{el}$
Approximate capital cost	dep. on use case and market environment, ca. EUR 4,000-5,000 per kW$_{el}$ (fully installed)
OEMs, system integrators	FuelCell Energy, AFC Energy – (Bloom Energy, Doosan, etc.)
Fuel cell suppliers	Nedstack, FuelCell Energy, AFC Energy (Bloom Energy, Doosan, etc.)
Typical customers	Utilities, ESCOs, energy-intensive industrial manufacturers, wastewater treatment operators, data centre operators, etc.
Competing technologies	Gas boilers + power grid, combustion engines, micro-turbines

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1) Focus on European market

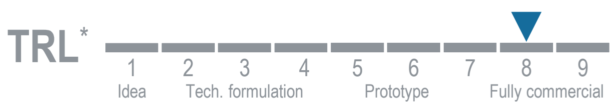
Source: Roland Berger

Readiness of FC in industrial use cases is increasing in Europe and catching up to North America and East Asia

Fuel cells in industrial and other large-scale stationary use cases

2/4

Overall technological readiness: Mature technological readiness as typical use cases (e.g. power generation, CHP) near commercialisation, growing number of demonstration projects and installations – market even more mature in North America and East Asia (more projects, more OEMs)



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Installation example of large scale fuel cell system at Friatec AG	🇩🇪	2015	Deployment of 1.4 MW fuel cell system at production facility of Friatec AG meeting 60% of power need of manufacturing process	n.a.
Installation of SOFC fuel cells in Osaka wholesale market[1]	🇯🇵	2015	Installation of 1.2 MW fuel cell system at Osaka Prefectural Central Wholesale Market supplying 50% of buildings energy needs, subsidised by Japan's Ministry of Environment	n.a.
Demonstration of large SOFC system fed with biogas from WWTP (DEMOSOFC)	🇪🇺	2015	Large scale (3 x 50 kW_{el}) fuel cell CHP plant demonstration in using biogas from a wastewater treatment facility (no commercial building application as such, but relevant for this power range)	EUR 5.9 m
Demonstration of CHP 2 MW PEM fuel cell (DEMCOPEM)	🇨🇳 🇪🇺	2015	Design, construction and demonstration of 2 MW PEM fuel cell power plant to be integrated into a chlorine production plant, objective is to reach competitive electricity price until 2020	EUR 10.5 m
Demonstration of large scale alkaline fuel cell system (POWER-UP)	🇪🇺	2013	Installation of 500 kW alkaline fuel cell system with heat capture to demonstrate automated and scaled up manufacturing capabilities of cost-effective industrial fuel cell components	EUR 11.5 m

[1] From a use-case point of view, this could be considered as a commercial building FCH application as well. Listed here due to power output of 1.4 MW

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Typically, specific industrial processes and less the power and heat requirements of the site itself create the use case for fuel cells

Fuel cells in industrial and other large-scale stationary use cases

3/4

Use case characteristics

Stakeholders involved	> OEMs of FC CHP systems, FC suppliers > Project developers, plant engineers, installers > Utilities, ESCOs, power/gas grid operators > Industrial facility operators, e.g. chemical production or wastewater treatment
Demand and user profile	> Electricity- and/or heat-intensive industrial processes (usually high-temp. heat), relatively constant load > On-site availability of fuel (e.g. biogas from anaerobic digesters, hydrogen as chemical byproduct) creating opportunity for distributed electricity / CHP generation
Deployment requirements	> Connection to the natural gas grid <u>or</u> on-site supply of biogas or hydrogen > Sufficient space for distributed energy solution (suitable on-site energy system)
Key other aspects	> Different use cases have different technical requirements for FC systems – the industrial process individually determines the application of a stationary fuel cell

Benefit potential for regions and cities

Environmental	> Low emissions of pollutants and greenhouse gases (esp. CO_2) – significant reduction CO_2, virtual elimination of NO_x and SOx emissions, reduction of primary energy consumption > Low noise pollution due to almost silent operation
Social	> Promotion of distributed energy systems, lowering social cost of electricity grid expansion esp. by DSOs > Enabler for more renewables in electricity mix with complementary role of distributed CHP to e.g. heat pumps
Economic	> With reduction of product cost and higher electrical efficiencies, TCO-competitiveness with other distributed energy solutions in reach – esp. in markets with high industrial electricity prices / spark spread (difference of gas and electricity prices)
Other	> Reduction of demand for centrally generated electricity > Higher resilience against interruption of grid electricity supply

Source: Roland Berger

High initial investment cost still primary economic barrier to extensive commercialisation, technical improvements key as well

Fuel cells in industrial and other large-scale stationary use cases

4/4

Hot topics / critical issues / key challenges:

> Identification of promising early-stage use cases ("early adopters"), e.g. in advantageous policy and market environments (e.g. CHP support schemes, strict local NO_x emission limits)

> Further reduction of capital cost through economies of scale necessary for widespread adoption

> Further technical performance improvements, e.g. increasing electrical efficiency (possibly up to $60\%_{el}$) increasing the robustness and reliability of fuel cell stacks

> Lack of component standardisation along value chain, further efforts to modularise systems to maximise cost-down potential per kW installed

Further recommended reading:

> "Advancing Europe's energy systems: Stationary fuel cells in distributed generation": http://www.fch.europa.eu/studies

> “Business models and financing arrangements for the commercialisation of stationary applications of fuel cells report” (forthcoming): http://www.fch.europa.eu/studies

> DEMOSOFC project website

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

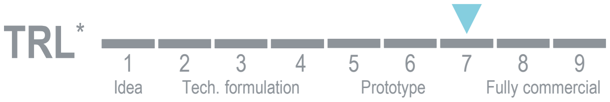
https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Large-scale stationary fuel could also be used to supply district heating grids – First demonstration projects in Asia

Excursus: large-scale stationary fuel cells for district heating

Brief description: Large scale (i.e. multi-MW) stationary fuel cell applications for combined heat and power generation (CHP) can be also used to supply local district heating networks; they are fuelled by natural gas and would typically use high-temp. MCFC or SOFC technology



Use cases: Cities and regions can deploy or incentivise the deployment of large scale stationary fuel cells for existing or new local district heating networks – especially in urban areas with strict limits for local CO_2 and NO_x / SO_x emissions; they could replace large CHP gas engines or small gas turbines; operators would typically be municipal utilities or energy service companies

Existing deployment projects (selection)

Project/product	Country	Since	Specifications
Noeul Green Energy Plant	🇰🇷	2017	A 20-MW MCFC fuel cell plant in Seoul, delivered by FuelCell Energy and POSCO Energy, owned and operated Korea Hydro & Nuclear Power (KHNP), supplying power for ca. 43,000 household to Korea Power Exchange and heat for ca. 9,000 households to Korea District Heating Co
Gyeonggi Green Energy Facility	🇰🇷	2014	A 59-MW fuel cell park in Hwasung City, consisting of 21 2.8-MW MCFC stationary fuel cells; supplied by FuelCell Energy, owned and operated by POSCO Energy

ⓘ **For additional information, please contact our Roland Berger team directly**

Source: Roland Berger

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Fuel cell powered back-up systems have a strong value proposition by flexibly safeguarding security of supply during power failures

Fuel cell powered back-up systems

1/4

Brief description: Fuel cell powered back-up systems for uninterrupted power supply (UPS) use (typically) compressed hydrogen gas as a fuel to generate electricity via a fuel cell-based energy converter to act as bridges during prolonged power failures

Use Case: Cities and regions can promote fuel cell powered back-up electricity systems to improve reliability and quality of power supply for critical infrastructure (e.g. data centers, hospitals, public security) with a local zero-emission technology alternative, typically for bridging time of up to 72 hrs

Fuel cell powered back-up system for uninterrupted power suplpy (UPS)

Key components	Fuel cell stacks, system module, hydrogen tank, battery (hybridised systems)
Fuel cell technology	Proton exchange membrane (PEM)
Fuel	Hydrogen
Electrical efficiency (net)	25up to 50% FC, possibly higher in the future
Output¹⁾	0.2 kW_{el} – 8.8 kW_{el}
Approximate capital costs	n.a.
Original Equipment Manufacturers	Plug Power, Ballard, Proton Motor
Fuel cell suppliers	Hydrogenics, Ballard Power Systems
Typical customers	Telecom providers, hospitals, municipal emergency services, municipal utilities
Competing technologies	Batteries, combustion/diesel generators

1) Based on Plug Power portfolio

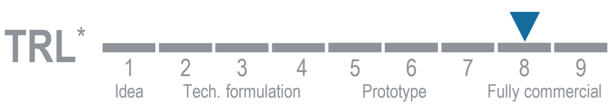
Source: Roland Berger

Even though several demo & commercial projects have confirmed the proof-of-concept, large scale deployment is still pending

Fuel cell powered back-up systems

2/4

Overall technological readiness: Various demonstration projects have shown technological maturity; high capital costs remain a barrier for widespread adoption, despite principle benefits compared to e.g. diesel-generator systems



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Federal Agency for Digital Radio of Security Authorities and Organisations (BDBOS)	🇩🇪	2012	Trial of more than 100 fuel cell back-up systems to power digital radio communication network used by German police and fire services (bridging time of up to 72 hours)	n.a.
Denmark Public Safety Network (SINE)	🇩🇰	2010	Installation and operation of fuel cell backup power systems at 120 radio base station sites throughout the Denmark SINE emergency service network	n.a.
Field test for portable generators, back-up and UPS power systems (FITUP)	🇪🇺	2010	Installation of 19 market-ready fuel cell systems as UPS/back-up power sources for customers in telecom and hotel industry with power levels in 1-10 kW range, demonstration of technical performance to accelerate commercialisation in Europe (coordinated by EPS)	EUR 5.3 m

Products / systems available (selection)

Name	OEM	Product features	Country	Since	Cost
GenSure	Plug Power	PEM fuel cell generator capable of delivering 150W of electrical power, hydrogen is delivered in standard steel cylinders	🇺🇸	n.a.	n.a.
Fcgen-H2PM	Ballard	Fuel cell backup power solution for outdoor operation as used for Denmark's emergency radio communication system	🇨🇦	n.a.	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Due to its flexibility, FC powered back-up systems have the potential to benefit a large range of (especially energy-critical) infrastructure

Fuel cell powered back-up systems

3/4

Use case characteristics

Stakeholders involved

- Telecom providers, datacenters as well as public institutions like schools, hospitals, prisons etc.
- Hydrogen suppliers
- Permitting and licensing authorities

Demand and user profile

- Typically critical infrastructure depending on security of electricity supply and very rapid, flexible reaction to shortages/outages in supply (e.g. data centers)

Deployment requirements

- Hydrogen production and delivery services
- Appropriate hydrogen storage infrastructure

Key other aspects

- Operation under all weather conditions as self-start in low temperatures possible

Benefit potential for regions and cities

Environmental

- Zero emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2)
- Low noise pollution due to almost silent in operation
- No risk of diesel spillage

Social

- Guarantee of municipal emergency services and critical infrastructure

Economic

- Cost saving potential compared to conventional diesel generators with lower service/maintenance costs – prospectively also lower fuel costs
- No need to replace fuel as frequently (contrary to diesel generator applications)

Other

- Increased reliability to start
- Modular scalability ensures flexible adaptation according to demand

Source: Roland Berger

System standardisation and the refining of the value proposition are key topics on the industry side

Fuel cell powered back-up systems

4/4

Hot topics / critical issues / key challenges:

> Clear value proposition as pure back-up vs. hybrid or distributed generation solutions given relatively low system average interruption durations across Europe (e.g. compared to North America)

> Lack of component standardisation across stationary fuel cell industry to advance cost reduction

> Limited EU-wide rules and standards for hydrogen storage and transport in order to safeguard quality requirements

> High requirements regarding purity level of hydrogen needed for fuelling back-up system

> Further reduction of capital cost through economies of scale necessary for large scale implementation of back-up systems

Further recommended reading:

> Fuel cells in uninterruptible power supply: http://www.fuelcelltoday.com/media/1637153/using_fc_uninterruptible_power_supply.pdf

> Stationary fuel cells in distributed generation: https://www.rolandberger.com/de/Publications/pub_advancing_europe_s_energy_systems.html

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Fuel cells can act as a reliable, versatile and flexible off-grid power source in various remote areas

Fuel cell off-grid power / isolated microgrids

1/4

Brief description: stationary fuel cells for off-grid or isolated microgrids provide base-load (or backup) electricity from hydrogen (or hydrocarbons) via a fuel cel); fuel cells are frequently combined with electrolyzers for power-2-hydrogen from renewables – as integrated end-to-end off-grid solutions

Use cases: Cities and regions can promote stationary fuel cells for off-grid power supply e.g. on islands, alpine villages, otherwise remote settlements currently dep. on on-site generation from fossil fuels – alternative e.g. to diesel generators to reduce emissions and even complement renewable energy sources

Fuel cell powered off-grid power

Key components	Stationary fuel cell: fuel cell stacks, system module, hydrogen or other fuel tank, battery (possibly heat exchanger)
Fuel cell technology	PEM, SOFC, AFC
Fuel	Likely hydrogen (possibly also natural gas, biogas, LPG)
Electrical efficiency (net)	up to 50% (PEM) or even 60% (SOFC)
Output	typically 5 – 250 kW_{el}, (potentially combined to larger systems)
Approximate capital cost	*TBD* – current FCH2 JU objective 4,500 EUR/kW_{el}
OEMs	BOC, Young Brother, Toshiba , EPS, Green Hydrogen, Atawey
Fuel cell suppliers	Ballard, Hydrogenics, EPS, EWII, Proton Motor, Sunfire, ITM
Typical customers	Telecom providers, municipalities in remote areas (e.g. islands, alpine regions), remote industrial facilities
Competing technologies	Fossil-fuel generators with internal combustion engines

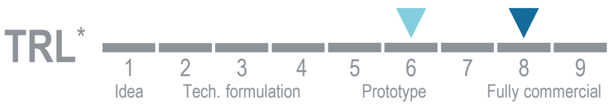
Source: Roland Berger

Various demonstration projects are underway to show the viability of off-grid applications in varying environmental settings

Fuel cell off-grid power / isolated microgrids

2/4

Overall technological readiness: Proven technology for stationary applications outside of Europe (key markets in North America and East Asia), European segment in advanced-prototype/demonstration phase with commercial viability being demonstrated in ongoing projects



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Demonstration of fuel cell-based energy solutions for off-grid remote areas	🇪🇺	2017	Demonstration of technical and economic viability of fuel cell technologies generating electrical energy in off-grid or isolated micro-grid areas	*TBD*
Electrolyzers for operation with off-grid renewable installations (ELY4OFF)	🇪🇺	2016	Demonstration of autonomous off-grid fuel cell systems as energy storage or back-up solutions to replace diesel engines (50 kW PEM electrolyser to work along existing renewable electricity, H_2-storage and stationary fuel cell)	EUR 2.3 m
Micro-CHP FC system for off-grid (FLUIDCELL)	🇪🇺	2014	Proof of concept and validation of advanced high performance micro-CHP fuel cell system for decentralised off-grid operation	EUR 4.2 m
Integrated Off-Grid Generator Application in remote, extreme-temp environment	🇷🇺	n/a	Installation of an off-grid power generator field application of ~4 kW CHP SOFC system by Sunfire for power supply along natural gas pipelines (Ural Mountains)	EUR 4.2 m

Products / systems available (selection)

Name	OEM		Product features	Country	Since	Cost
Hymera	BOC	BOC A Member of The Linde Group	PEM fuel cell generator capable of delivering 150 W of electrical power, hydrogen is delivered in standard steel cylinders	🇬🇧	n.a.	n.a.
H2One	Toshiba	TOSHIBA	Hydrogen-based autonomous off-grid energy supply system with use cases ranging from power supply to load management	🇯🇵	n.a.	n.a.

Source: Roland Berger

*) Technology Readiness Level ▽ ≤ 5 ▽ 6-7 ▼ 8-9

Besides proving operability under all weather conditions, the modular design allows for flexible scalability of electrical output

Fuel cell off-grid power / isolated microgrids

3/4

Use case characteristics

Stakeholders involved	> Municipal authorities and utilities in remote areas such as islands or alpine regions > Industrial sites with limited access to grid power, telco operators
Demand and user profile	> Base-load power supply > Backup power supply, especially when combined with on-site hydrogen supply from renewables via electrolyzer
Deployment requirements	> Hydrogen production, delivery and on-site storage – potentially critical for remote areas > Combination with on-site hydrogen production (e.g. water electrolysis from renewables)
Key other aspects	> Operation under all weather conditions possible for most fuel cells, e.g. incl. self-start in low temperatures

Benefit potential for regions and cities

Environmental	> Zero local emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2) > Low noise pollution due to almost silent operation
Social	> Reliable power supply in remote areas > Additional security of power supply for critical industrial processes
Economic	> Low operating cost through long lifetime and minimal need for regular/predictive maintenance visits – long-term potential for TCO below diesel generators > Potential cost benefit compared to grid connection or grid expansion
Other	> Modular scalability ensures flexible adaptation according to demand

Source: Roland Berger

Overcoming the lack of hydrogen infrastructure/supply in remote areas is potentially the biggest implementation challenge

Fuel cell off-grid power / isolated microgrids

4/4

Hot topics / critical issues / key challenges:

> Lack of hydrogen infrastructure/supply in remote areas – hydrogen has to be delivered (e.g. trucked) or produced on site (or other fuels have to be made available on site, e.g. natural gas along pipelines)

> Further reduction of capital cost through economies of scale necessary for large scale implementation of off-grid power systems

> Lack of component standardisation within value chain (similar for a number of stationary fuel cells)

> Limited EU-wide rules and standards for hydrogen storage and transport in order to safeguard quality requirements

Further recommended reading:

> Hydrogen and fuel cells for communities: https://www.ika.rwth-aachen.de/r2h/images/b/b1/HC_HandbookVolA150.pdf

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

E. WG5: "Energy-to-hydrogen applications"

Working Group 5 covers a selection of key hydrogen production technologies and non-transport/stationary usages

Working Group 5: Energy-to-hydrogen applications[1]

Hydrogen production:

1. Focus on electrolysis, basic comparison with conventional methods - Green hydrogen production/power-to-hydrogen

"Hydrogen-to-X:"

2. Energy storage (refer to E.1)
3. Hydrogen injection into the gas grid
4. Electricity grid services

52 regions & cities are part of the Working Group 5 from **17** European countries

17 industry participants are now part of Working Group 5 from **6** European countries

AFC Energy, Air Liquide, ariema, Fronius, eps, storengy, Logan Energy, sunfire, HYDROGENICS, SEMA consulting, HyET Hydrogen, BOC, H2B2, ITM POWER, SOLID POWER, uniper, CALVERA Hydrogen

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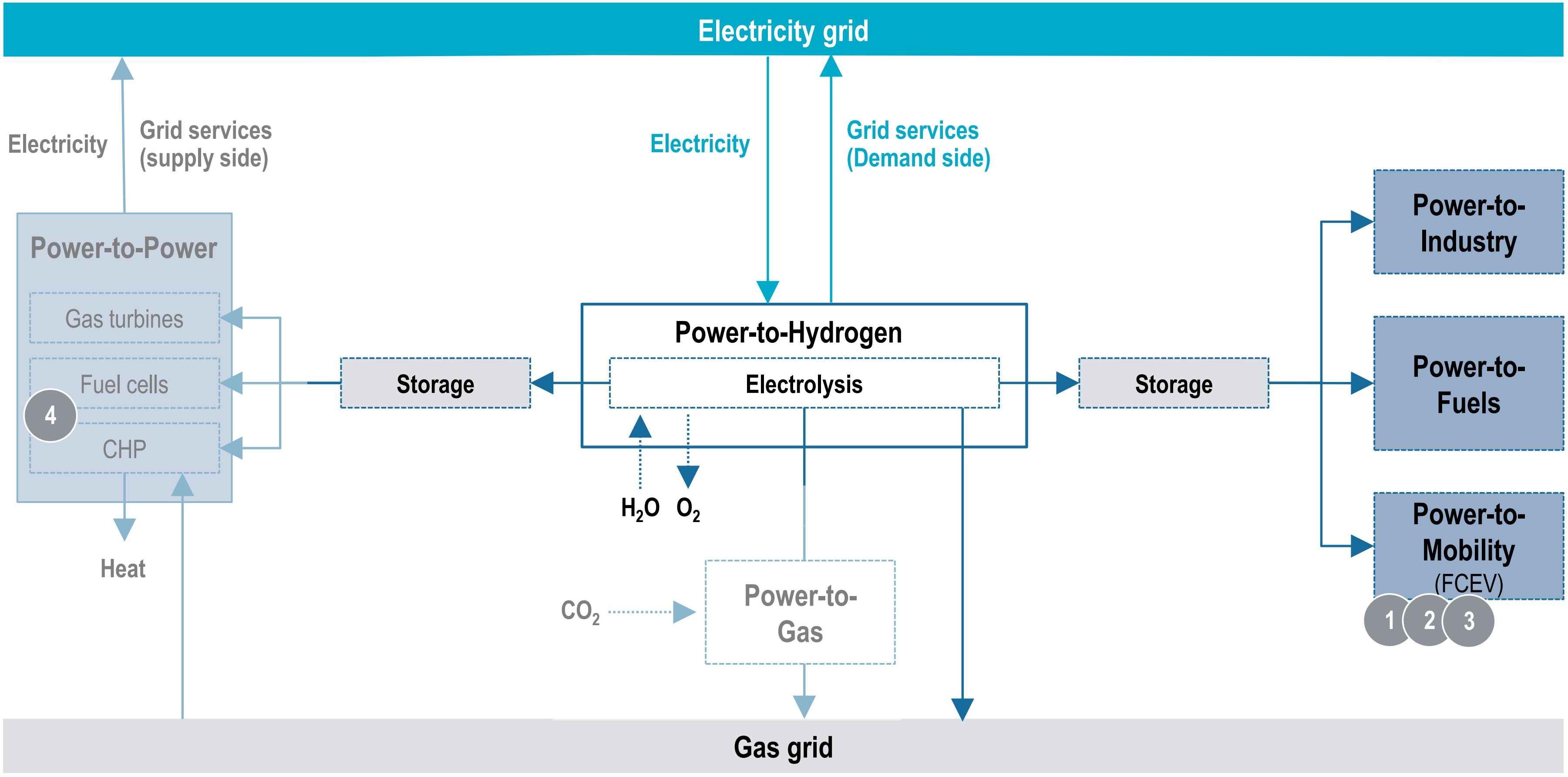
1) Selection of applications based on revised scope of the 2016-17 FCH2 JU study "Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities"

Complementing WG1-4, WG5 shall tackle hydrogen supply, storage (focus on "green" hydrogen) as well as secondary services

Market structure and focus of WG 5 – SIMPLIFIED, ILLUSTRATIVE



▨ Hydrogen offtake (revenue sources) ▨ Storage (for time decoupling) ▨ Electricity input (cost reduction through grid balancing) Ⓧ Covered by other Working Group

Source: FCH2 JU, Sunfire, Hydrogenics, Roland Berger

Electrolysers produce hydrogen from renewable energy electricity with significantly less emissions than conventional technologies

Power-to-Hydrogen / "green hydrogen"

1a/4

Brief description: "Green hydrogen" production technologies produce hydrogen via an electrolyser using electricity from renewable energy sources and are therefore more sustainable than conventional hydrogen production technologies

Use cases: Cities and regions can use/promote green hydrogen production to provide a wide spectrum of services ranging from various grid services or energy storage to hydrogen refuelling stations or industrial use

Power-to-Hydrogen / production of "green hydrogen"[1]

Key components	Connection to electricity grid, electrolyser, storage facility, offtake interface, fuel cell if applicable
Electrolysis type / principle	Alkaline, Proton Exchange Membrane, (Solid Oxide)
Power consumption (1-20 MW)	51-63 kWh/kg
Tap water requirement	15 L/kg
CAPEX (1-20 MW plant size)	750 – 1,500 EUR/kW
OPEX (1-20 MW plant size)	2-4% of CAPEX
Original Equipment Manufacturers	Areva, H2B2, H2 Nitidor, Hydrogenics, Hygear, ITM Power, NEL Hydrogen, McPhy, Siemens, Sunfire, EPS, Fronius
Typical customers	Dependent on H_2 use/offtake, e.g. HRS operators, industry, TSOs, DSOs[2)], natural gas network
Competing technologies	SMR, Biogas SMR, Industrial by-product hydrogen

1) Technology details based on FCH 2 JU study: "Study on early business cases for H2 in energy storage and more broadly power to H2 applications"; June 2017
2) Transmission System Operator / Distribution System Operator

Source: FCH 2 JU, Roland Berger

Alkaline (ALK) and Proton Exchange Membrane (PEM) are the most common electrolyser technologies in the market

Key figures of Power-2-Hydrogen technologies (as of 2017)

1b/4

		Alkaline electrolysis (ALK)						**Polymer electrolyte membrane electrolysis (PEM)**					
		2017 @ P atm			**2025 @ 15 bar**			**2017 @ 30 bar**			**2025 @ 60 bar**		
	Units	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW
Minimum power	% Pnom	15%			10%			5%			0%		
Peak power – for 10 min	% Pnom	100%			100%			160%			200%		
Pressure output	Bar	0 bar			15 bar			30 bar			60 bar		
Power consumption @ P nom	kWhe/kg	58	52	51	55	50	49	63	61	58	54	53	52
Water consumption	L/kg	15 L/kg											
Lifetime – system	Years	20 years											
Lifetime – stack @ full charge	hr	80,000 h			90,000 h			40,000 h			50,000 h		
Degradation – system	%/1000 h	0.13%/1,000 h			0.11%/1,000 h			0.25%/1,000 h			0.20%/1,000 h		
Availability	%/year	>98%											
CAPEX – total system equipment	EUR/kW	1,200	830	750	900	600	480	1,500	1,300	1,200	1,000	900	700
OPEX – electrolyser system	% CAPEX	4%	3%	2%	4%	3%	2%	4%	3%	2%	4%	3%	2%
CAPEX – stack replacement	EUR/kW	420	415	338	315	300	216	525	455	420	300	270	210

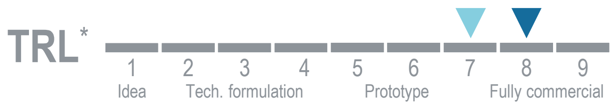
Source: FCH2 JU

Numerous demonstration projects have already been deployed all over Europe using various electrolyser technologies

Power-to-Hydrogen / "green hydrogen"

2/4

Overall technological readiness: Depending on technology used, system in prototype phase or at pre-commercial / commercial stage; given the significant interest from industry and policy makers alike, there are significant efforts in demonstration projects and deployment initiatives all over Europe



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project budget
H2Future	🇦🇹	2017	One of the biggest green hydrogen production sites worldwide; 6 MW PEM electrolyser, funded by FCH 2 JU with EUR 12m. Hydrogen used for industrial use and for balancing the power reserve market	EUR 18 m
Ingrid	🇮🇹	2016	1.2 MW Alkaline electrolyser for renewable energy electricity with a solid hydrogen storage system and a fuel cell for re-electrification and other use cases	n.a.
GrInHy	🇩🇪	2016	Production of green hydrogen for a Steel Company. Solid oxide electrolyser cell (SOEC) with 80% efficiency, 40 Nm^3 H_2/h output	EUR 4.5 m
European Marine Energy Centre (EMEC)	🇬🇧	2015	Storage capacity of 500 kg compressed hydrogen; 0.5 MW PEM electrolyser with integrated compression absorbs excess energy from tidal turbines	n.a.
Mainz Energy Farm	🇩🇪	2014	6 MW, high-pressure PEM electrolyser with targeted output of 200t H_2/year; Power from windfarms	n.a.
Jupiter1000	🇫🇷	2014	Demonstration project of renewable energy electricity storage in a transmission gas grid via Alkaline and PEM electrolysers of 0.5 MW each. Commissioning and start-up in 2018	n.a.
WindGas Falkenhagen	🇩🇪	2013	Production of 360 Nm^3 H_2/h green hydrogen from wind energy via 2 MW electrolysers in Falkenhagen. Injection of hydrogen into gas grid	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Power-to-hydrogen enables use of excess electricity and presents environmental friendly way of producing hydrogen

Power-to-Hydrogen / "green hydrogen"

3/4

Use case characteristics

Stakeholders involved	> Energy supplier, TSO, DSO > Operator of electrolyser and ancillary infrastructure (if applicable) > Public authority (e.g. regulator, etc.) > H_2 consumer (if applicable)
Demand and user profile	Various options depending on the subsequent use of the hydrogen: > use of base-load electricity > use of peak load electricity > use during times of low electricity prices
Deployment requirements	> Intermittent renewable energy sources nearby > Adequate downstream infrastructure (e.g. satisfactory storage facility or connection to the gas grid or H_2 consumer)
Key other aspects	> n/a

Benefit potential for regions and cities

Environmental	> Optimal use of generated excess electricity that would otherwise be wasted > Depending on the subsequent use of hydrogen significant reduction in emissions as green hydrogen is produced and used
Social	> Reduced retail electricity prices as cost for re-dispatch reduce with large-scale deployment. Therefore positive effects for especially low income households that are increasingly affected by rising electricity prices > Increased stability of power supply if hydrogen is also used for grid services
Economic	> Price arbitrage opportunity based on production during low energy price periods and re-electrification during higher price periods > Depending on regulatory framework, opportunity for additional revenues if green hydrogen is used for power-to-power grid services, for example frequency restoration reserve
Other	> Depending on the country and its regulation, feed-in tariffs exist for the re-electrification of green hydrogen

Source: Roland Berger

Total electricity cost and hydrogen prices as critical issues for the development of the green hydrogen market

Power-to-Hydrogen / "green hydrogen"

4/4

Hot topics / critical issues / key challenges:

> Cost competitiveness (cost of electrolysers not yet competitive with conventional hydrogen production like SMR or hydrogen as industrial by-product because of high production cost)

> Increasing technical performance (higher efficiencies will enable significantly lower OPEX and thus, higher allowable electricity prices, making the case even with higher initial CAPEX)

> Regulation (highly regulated electricity market which is not harmonised within the European Union; various regulatory measures and challenges for grid services supply; access regulation to curtailed electricity unclear)

> Total electricity cost as key input factor (rising electricity cost reduce competitiveness; business case highly dependent on electricity prices)

> System size (influences the project CAPEX and equipment related OPEX)

> Development of hydrogen prices (influences the potential revenue a green hydrogen production plant can generate)

> Potential levelling of feed-in tariffs for injecting into the gas grid for hydrogen compared to biogas

Further recommended reading:

> FCH 2 JU: "Study on early business cases for H2 in energy storage and more broadly power to H2 applications"; June 2017 http://www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCHJU.pdf

> FCH 2 JU: "Commercialisation of Energy Storage in Europe"; March 2015 http://www.fch.europa.eu/sites/default/files/CommercialisationofEnergyStorageFinal_3.pdf

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

To decouple supply and demand if necessary, several storage options for hydrogen exist

Excursus: hydrogen storage and hydrogen as medium for energy storage

Excursus

> **In order for energy-to-hydrogen applications to effectively bridge time differences** between economically attractive power-to-hydrogen production (e.g. low electricity prices, need for curtailment of power generation from renewables, etc.) and hydrogen usage/offtake and in order for such applications to deliver full energy storage services, green hydrogen needs to be temporarily stored

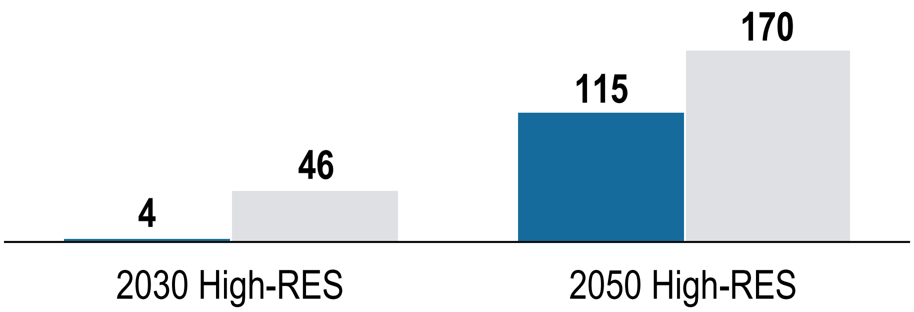
> **Two types of storage infrastructure are in principle available**, their suitability depends among others on the intended final use of the hydrogen, the scale of production, spatial considerations, etc.:

- **Dedicated hydrogen (gas) storage infrastructure**
  - Small-scale storage (cylinders and bundles): small quantities of fuel storage
  - Mid-scale storage (storage tanks): medium quantities of fuel storage (e.g. at hydrogen refueling stations)
  - Large-scale storage (caverns): large quantities of fuel storage (e.g. for large-scale use in power production, chemical industry plants); typically long lead times for construction (e.g. due to permitting process) and relatively high investment cost
- **Natural gas infrastructure**, if hydrogen is either directly injected into gas grid or indirectly via a power-to-gas process:
  - Gas transmission and distribution grid (high- and low-pressure gas pipelines)
  - Underground Gas Storage (UGS) facilities – mainly depleted gas fields (68%), aquifers (15%), salt caverns (15%) – with a total technical working gas volume of ~1,180 TWh across the EU-28 as of 2016
  - Usage of energy stored hence generally limited to gas applications (gas-fired power plants, gas boilers, etc.)

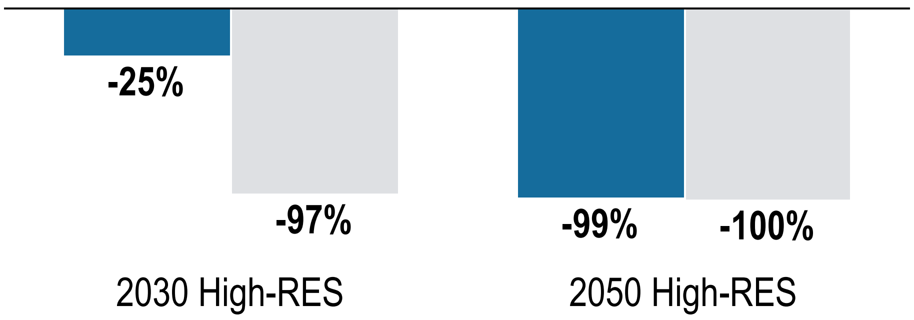
Source: GIE, Roland Berger

Demand and economic viability of P2H depend on the future price of H2 – results based on previous FCH2 JU study (2015)

Economic demand[1] for electrolyzers assuming a best case of EUR 2 per kg of H2 [GW]



Reduction in excess energy [%]



⬚ Germany archetype ■ High connectivity ■ Low connectivity

- Non-hydrogen P2P and heat storage will only be able to absorb a small part of the excess energy generated, resulting in the necessity of curtailment – from societal point of view, such electricity could be used at close to zero cost
- The excess energy can be used to produce hydrogen via water electrolysis for re-electrification or use outside of the power sector
- If the value of hydrogen at the point of **production can reach a price in the range of EUR 2-4 per kg very large installed electrolyzer** capacity would be economically viable and able to utilize nearly all of the excess electricity
- Such use of the excess electricity would create value for the society and the surplus could be divided between the electricity and hydrogen producer

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[1] Installed electrolyzer capacity achieving EUR 60 / installed kW per year of benefits at given hydrogen plant gate cost – This corresponds to EUR 370/kW capex, 8% WACC, annual opex at 1.2% of total capex and 10 years lifetime (FCH JU 2014) – Assumes electricity for free, no grib connections fees and no time-shift storage is in place

Source: FCH2 JU study "Commercialisation of Energy Storage in Europe" (2015)

Bankable business cases in three exemplary locations were identified – results based on previous FCH2 JU study (2017)

WACC on CAPEX: 5% *Project lifetime: 20 years*	**SC mobility (Albi, France)**		**Light industry (Trige Denmark)**		**Large industry (Lubeck, Germany)**	
	2017	**2025**	**2017**	**2025**	**2017**	**2025**
Primary market H2 volume (t/year)	270	950	900	900	3,230	3,230
Average total electricity price for primary market [EUR/MWh]	44	45	38	47	17	26
Net margin without grid services [EUR k/MW/year]	39	71	228	248	-146	30
Net margin with grid services [EUR k/MW/year]	159	256	373	393	-13	195
Share of grid services in net margin [%]	75%	72%	39%	37%	–	85%
Payback time without grid services [years]	**11.0**	**9.0**	**4.6**	**3.7**	**–**	**8.4**
Payback time with grid services [years]	**8.0**	**4.5**	**3.4**	**2.7**	**–**	**3.5**
Key risk factors	> Taxes & grid fees > H2 price > Size of fleets > Injection tariff > FCR value		> H2 price > Taxes & grid fees > FCR value		> Taxes & grid fees > FCR value > Carbon price	

⬚ Germany archetype

- > By 2025, the European market for P2H is estimated at a cumulative 2.8 GW, representing a market value of EUR 4.2 bn
- > Study launched on 23rd June 2017 in Brussels, also available at FCH2 JU website

Source: FCH2 JU study "Study on Early Business Cases for H2 in Energy Storage and more broadly Power to H2 Applications" (2017)

Hydrogen into gas grid applications provide a sustainable solution for renewables-based storage and transformation of energy grids

Hydrogen into gas grid

1/4

Brief description: Hydrogen can be converted from renewable energy sources and injected into existing natural gas grids for initial (or long-term) storage and subsequent use in a range of different applications (power generation, heat provision, transport applications such as gas-fuelled urban buses or passenger cars)

Use Case: Cities and regions can inject (or call for / incentivise the injection of) green hydrogen (i.e. from power-to-hydrogen P2H sources) into gas grids to further promote renewable energy sources, decarbonise the gas grid and provide long-term energy storage solutions

Fuel cells in commercial buildings

Key components	Electrolyser, fuel cell, blending/injection system
Electrolysis technology for P2H	Alkaline (ALK), PEM, (Solid Oxide)
H_2 production efficiencies	50-83 kW_{el}/kg (2013), 36-63 kW_{el}/kg (2030)
Cost of H_2 production for P2H	*dep. on electrolyser size, technology, power input price, etc.*
Maximum H_2 blend level	5 – 20% (potentially even 25%, dep. on gas infrastructure)
Hydrogen provider	E.on, RWE, Thüga
Gas distributors	Private and municipal utilities (e.g. German Stadtwerke), gas TSOs or DSOs
Typical customers	Public and private utilities, public and private TSOs or gas shippers, ultimately e.g. passenger car fleet operators
Competing technologies	Other energy storage (e.g. pump storage, batteries)

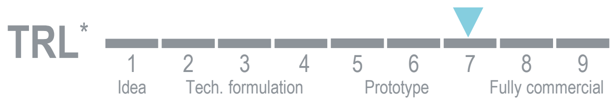
Source: Roland Berger, FCH2 JU

Several successful demonstration projects provide a valid foundation, also for the assessment of future commercialisation

Hydrogen into gas grid

2/4

Overall technological readiness: Large scale demonstration and lighthouse projects ongoing and more being commissioned, showcasing technical and economical viability of technology in a relevant operational environment (especially combination of P2H and injection into gas grid)



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
P2G Ibbenbüren demonstration plant (RWE)	🇩🇪	2014	Operation of 150 kW P2G demonstration plant producing green hydrogen to be injected into gas distribution network, grid operation by Westnetz GmbH	n.a.
WindGas Falkenhagen (E.ON)	🇩🇪	2011	Green hydrogen production from 2 MW wind power to be fed into gas distribution network, grid operation by Ontras Gastransport GmbH	n.a.
Network management by injecting hydrogen to reduce carbon content (GRHYD)	🇫🇷	2013	Phase 1: Two-year preliminary study adapting existing natural gas vehicle (NGV) fuelling station with new hydrogen/natural gas mixture (Hythane®) Phase 2: Five-year demonstration phase of hydrogen injection into natural gas distribution network with blend level of up to 20%	n.a.
HyDeploy	🇬🇧	2016	0.5 MW electrolyser to demonstrate the use of blended hydrogen in the UK gas grid	GBP 6.8m

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Besides supporting the integration of renewables, hydrogen-into-gas grids offers an efficient storage solution with existing infrastructure

Hydrogen into gas grid

3/4

Use case characteristics

Stakeholders involved

- Electricity generating utilities, e.g. operators of wind farms or larger solar PV parks
- Natural gas transmission system and distribution operators
- Regulatory and permitting authorities

Demand and user profile

- Utilisation of excess power from intermittent sources (e.g. PV, wind) to produce "green" hydrogen, on-site electrolyser, e.g. built into container for scalability
- Maximum H_2 blend level of gas grid as critical framework condition

Deployment requirements

- Hydrogen production and electrolysis
- Quality of (local or regional) gas grid infrastructure (e.g. material durability of meters)
- Adequate downstream infrastructure (e.g. satisfactory connection to H_2 consumer)

Key other aspects

- Facilitation of hydrogen infrastructure and wider adoption of mobile FC application such as FCEV

Benefit potential for regions and cities

Environmental

- Reduction of carbon footprint of natural gas grid and ultimately gas-fuelled energy and transport applications
- Improved flexibility for electricity system supporting the integration of renewable energy

Social

- Improved stability and security of energy supply, through a viable medium- and long-term storage opportunity
- Improve social acceptability of hydrogen and fuel cell applications – as larger component of an integrated transition of the energy system

Economic

- Shift of energy transport to gas pipelines and thus lower intensity of electricity grid expansion
- Efficient utilisation of existing natural gas infrastructure, especially in parts of Europe with high gas grid densities
- Short-term, medium-term and seasonal storage opportunities

Other

- Further promotion of renewable energy sources as a result of converted hydrogen being injected into gas grid and overall higher ability of electricity/gas system to absorb variable electricity generation from renewable sources

Source: Roland Berger

Among others, a lack of standardised gas composition, blend concentration and missing incentives inhibit large scale deployment

Hydrogen into gas grid

4/4

Hot topics / critical issues / key challenges:

- Appropriate hydrogen blend concentration may vary significantly between pipeline network systems and natural gas compositions (e.g. range of 5-25%)
- Additional pipeline monitoring and maintenance measures will likely be necessary, necessitating investments on the gas TSO/DSO's side
- Degrading durability of metal pipes and materials when exposed to hydrogen may require necessary infrastructure upgrades
- Lack of incentives and compensation systems to reward energy storage services is a key element of a commercial business case that is currently not clear enough (e.g. under German Renewable Energy Sources Act (EEG)) – revenue remuneration / monetisation streams have to defined

Further recommended reading:

- Study on Early Business Cases for H2 in Energy Storage and More Broadly Power to H2 Applications http://www.fch.europa.eu/studies
- Blending Hydrogen into Natural Gas Pipelines: https://energy.gov/sites/prod/files/2014/03/f11/blending_h2_nat_gas_pipeline.pdf
- Power-to-Gas system solution: http://www.powertogas.info/fileadmin/content/Downloads/Brosch%C3%BCren/dena_PowertoGas_2015_engl.pdf

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Electrolysers are already technically capable for services to stabilize the electricity grid and to generate additional revenues

Electricity grid services[1]

1/4

	Frequency Containment Reserve (FCR)	Frequency Restoration Reserve (FRR)	Replacement Reserve (RR)
Definition	FCR automatically and continuously regulates the positive and negative frequency fluctuations; electrolysers can support the system via increased/decreased demand	FRR can automatically or manually restore the frequency via operating reserves to replace FCR; electrolysers can support the system via increased/decreased demand	RR is used to restore the required level of operating reserves; supersedes FCR and FRR to be prepared for further disturbances in the grid
Suitable electrolyser technology 2)	PEM / Alkaline (until now, only tested under lab conditions)	PEM / Alkaline (when operated adequately)	PEM / Alkaline
Requirements	Activation time ≤ 30 s; utilisation for 15 min max; minimum bid size ±1 MW; 1 week commitment per auction	Activation time 2-15 min depending on country-specific regulations; no standardized technical requirements	Activation time (≥ 15 min) depending on country-specific regulations; no standardized technical requirements
Procurement	FCR activation is a joint action of all TSOs in Continental Europe; quite homogeneous technical requirements; joint procurement in Central Europe via auctions organised by TSOs	Fragmented regulation across the European Union; procurement via auctions organised by TSOs in various European countries	Fragmented regulation across the European Union, procurement via auctions organised by TSOs in various European countries

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1) Based on regulation in Continental Europe; power grid frequency of 50.00 Hz

2) Dependent on regulation and requirements in each country

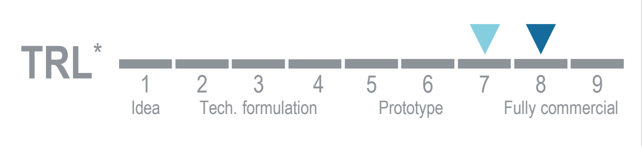
Source: FCH2 JU, Roland Berger

Numerous projects have already been deployed all over Europe using various electrolyser technologies for electricity grid services

Electricity grid services

2/4

Overall technological readiness: Depending on technology used, system in prototype phase or at pre-commercial / commercial stage; given the significant interest from industry and policy makers alike, there are significant efforts in demonstration projects and deployment initiatives all over Europe



Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Demo4Grid	🇦🇹	2017	Demonstration of 4MW pressurized alkaline electrolyser for grid balancing services under market conditions; demonstration site in Austria and project partners in ES, AT and CH; funded by the FCH2 JU with EUR 2.9 m	EUR 7.7 m
QualiGridS	🇩🇪	2017	Establishment of a standardised test for electrolysers performing electricity grid services; performance and business case analysis for (50 – 300 kW) PEM as well as Alkaline electrolysers; funded by the FCH2 JU with EUR 1.9 m and project partners in DE, NO, UK, FR, DK, NL and CH	EUR 2.8 m
H2Future	🇦🇹	2017	Joint project of energy suppliers, the steel industry, technology providers and research partners; 6 MW PEM electrolyser, funded by the FCH2 JU with EUR 12m. Hydrogen used for rapid response to provide grid balancing services and supply to hydrogen markets; project partners in AT, DE and NL	EUR 18 m
Ingrid	🇮🇹	2016	1.2 MW Alkaline electrolyser for renewable energy electricity with a solid hydrogen storage system and a fuel cell for flexibility services and grid balancing in general	n.a.
HyBalance	🇩🇰	2015	PEM electrolyser designed for combined operation providing both grid balancing services and hydrogen for industry and as a fuel for transport; funded by FCH2 JU with EUR 8 m; project partners in DE, DK, FR, BE	EUR 15 m
Myrte	🇫🇷	2010	PEM Electrolyser and storage system on the island of Corsica used for electricity grid services	n.a.

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: Roland Berger

Optimal use of renewable energy electricity and an additional revenue stream for plant operators as key potential benefits

Electricity grid services

3/4

Use case characteristics

Stakeholders involved	> Energy supplier, TSO, DSO > Operator of electrolyser and ancillary infrastructure (if applicable) > Public authority (e.g. regulator, etc.)
Demand and user profile	> Based on the type of electricity grid service supplied, quick activation time required > Reliability of technical equipment to operate in case of electricity grid fluctuations
Deployment requirements	> Various technical requirements depending on the type of electricity grid service supplied and the regulation in the specific country
Key other aspects	> n/a

Benefit potential for regions and cities

Environmental	> Optimal use of generated renewable energy electricity > Grid services supplied with hydrogen using electricity that has been generated via renewable energy; potentially replacing conventional plants that grid services
Social	> Reduced retail electricity prices as cost for re-dispatch reduce with large-scale deployment. Therefore positive effects for especially low income households that are increasingly affected by rising electricity prices > Increased stability of power supply
Economic	> Depending on regulatory framework, opportunity for additional revenues through supplying (negative or positive) operating reserve aside the revenues through hydrogen sales > Remuneration for grid services might rise in the coming years through the increasing share of fluctuating renewables in the electricity mix
Other	> Supplying electricity grid services can be seen as a "secondary revenue stream"; additional revenues on top of a primary revenue stream at low marginal cost

Source: Roland Berger

Cost competitiveness and regulation as key challenges for the supply of electricity grid services with electrolyser technologies

Electricity grid services

4/4

Hot topics / critical issues / key challenges:

> Increasing **technical performance** (higher efficiencies will enable significantly lower OPEX and thus, higher allowable electricity prices, making the case even with higher initial CAPEX; lower activation time needed to supply specific grid services)

> **Cost competitiveness** (electricity grid services mostly remunerated via auctions in the European Union, therefore direct competition with other suppliers through pay-as-bid auction)

> **Regulation** (highly regulated electricity grid services market which is only partly harmonised within the European Union; access to the market for electrolysers varies depending on the country)

> **Total electricity cost** as key input factor (rising electricity cost reduce competitiveness; business case highly dependent on electricity prices)

> **System size** (influences the project CAPEX and equipment related OPEX)

> **Remuneration for operating reserve** (through the liberalisation of the operating reserve market and the allowance of smaller bid sizes, remuneration decreased on average over the last years; however opposite developments possible with increasing share of renewables in the market)

Further recommended reading:

> FCH 2 JU: "Study on early business cases for H2 in energy storage and more broadly power to H2 applications"; June 2017: Link

> FCH 2 JU: "Commercialisation of Energy Storage in Europe"; March 2015: Link

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

F. Your contacts

Please do not hesitate to get in touch with us

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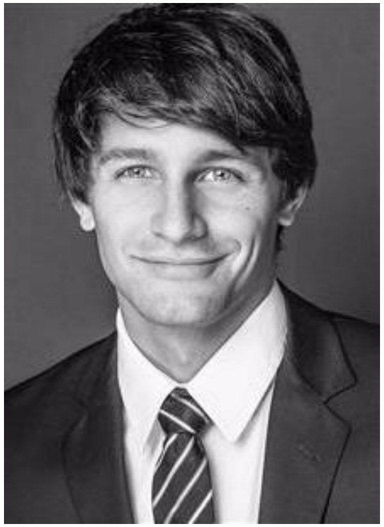

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G. Appendix

References

Pictures: Working Group 1

Application	Source/ Copyright
Fuel cell heavy-duty trucks / lorries	trucks.com (Toyota) nikolamotor.com
Fuel cell electric buses	fuelcellsworks.com
Fuel cell electric trains - Hydrails	alstom.com

References

Pictures: Working Group 2

Application	Source/ Copyright
Fuel cell electric vehicles - Cars	welt.de (alliance / dpa-tmn)
Fuel cell electric vehicles – Delivery vans	trucks.com (UPS) uesmfg.com
Fuel cell refuse garbage trucks	e-truckseurope.com
Fuel cell sweepers	newatlas.com

Application	Source/ Copyright
Fuel cell construction mobile equipment & tractor	symbiofcell.com inhabitat.com
Fuel cell powered material handling equipment	still.de
Fuel cell electric bikes	the-linde-group.com
Fuel cell electric scooters	globalsuzuki.com

References

Pictures: Working Group 3

Application	Source/ Copyright
Fuel cell powered boats	fuelcellsworks.com boatinternational.com
Fuel cell powered ships	elding.is ship-technology.com
Fuel cell powered ferries	bristolhydrogenboats.co.uk tu.no (BYstebo (CC BY-SA 3.0))
Fuel cell powered aircrafts	dlr.de

Application	Source/ Copyright
Fuel cell powered port operations equipment	evworld.com handyshippingguide.com http://www.terbergspecialvehicles.com/globalassets/news-and-media/media-impressions-700x438/pictures-yt/picture-gallery-
Fuel cell powered aircraft ground support equipment (GSE)	energy.gov

References

Pictures: Working Group 4

Application	Source/ Copyright
Fuel cell powered gen-sets	boconlineblog.co.uk
Fuel cell off-grid power	twitter.com/ICEEMSLtd
Fuel cell powered back-up system	plugpower.com
Fuel cells for residential use	sbz-online.de (Uwe Bolz)

Application	Source/ Copyright
Fuel cells in commercial buildings	worldarchitecturenews.com
Fuel cells in industrial use cases	fchea.org
Hydrogen-based district heating	thermcare.co.uk

References

Pictures: Working Group 5

Application	Source/ Copyright
Grid services	angloamerican.com (McKinsey) uniper.energy
Energy storage	mcphy.com uniper.energy
Demand management	itm-power.com pimagazine-asia.com
Frequency response	h2fc-fair.com sotaventogalicia.com

References

Data and Background Literature: Working Group 1 (1/2)

Application	Source
Fuel cell heavy-duty trucks / lorries	coop.ch nikolamotor.com ngtnews.com truckerplanet.net ushybrid.com energy.gov toyota.com carsofchange.com trucks.com greencarcongress.com calstart.org aqmd.gov

Application	Source
Fuel cell electric buses	greencarcongress.com smmt.co.uk fch.europa.eu ballard.com mercedes-benz.de toyota.com vanhool.be daimler.com now-gmbh.de

References

Data and Background Literature: Working Group 1 (2/2)

Application	Source
Fuel cell electric trains - Hydrails	alstom.com ballard.com hydrail.appstate.edu welt.de iphe.net Expert Interview with Dr. Robinius railwaygazette.com railengineer.uk hydrogenics.com sze.hu trid.trb.org jreast.co.jp rssb.co.uk

References

Data and Background Literature: Working Group 2 (1/4)

Application	Source
Fuel cell electric vehicles - Cars	h2me.eu cleanenergypartnership.de faz.net toyota.de airliquide.com contracthireandleasing.com afcc-auto.com cafcp.org RB H2 Marktstudie Strategie manager-magazin.de

Application	Source
Fuel cell electric vehicles – Delivery vans	fleetsandfuels.com uesmfg.com hydrogen.energy.gov valence.com h2me.eu tenerrdis.fr hybridcars.com online.anyflip.com kooperation-international.de

References

Data and Background Literature: Working Group 2 (2/4)

Application	Source
Fuel cell refuse garbage trucks	waterstofnet.eu lifeandgrabby.eu recyclingportal.eu e-truckseurope.com ulemco.com hyer.eu investinfife.co.uk ulemco.com ngvjournal.com greenmotorsblog.de berlin-klimaschutz.de bsr.de technomar.de

Application	Source
Fuel cell sweepers	novinite.com netinform.de studylib.net usfuelcell.com swissinfo.ch worldsweeper.com fuelcellsworks.com hydrogencarsnow.com hydrogenics.com hidrogenoaragon.org zerohytechpark.eu ushybrid.com fleetsandfuels.com etoltec.co.uk sweeper.buchermunicipal.com technomar.de

References

Data and Background Literature: Working Group 2 (3/4)

Application	Source
Fuel cell construction mobile equipment & tractor	symbiofcell.com ivtinternational.com nuvera.com newholland.co.nz fwi.co.uk autodesignmagazine.com

Application	Source
Fuel cell powered material handling equipment	prnewswire.com nrel.gov energy.gov markets.ft.com ir.plugpower.com fch.europa.eu h2bz-hessen.de flurfoerderzeuge.de lindeus.com linde-mh.com nuvera.com plugpower.com ballard.com Hydrogen Energy Engineering: A Japanese Perspective bendigomitchell.com

References

Data and Background Literature: Working Group 2 (4/4)

Application	Source
Fuel cell electric bikes	diva-portal.org irunonhydrogen.com newsroom.unsw.edu.au gernweit.com clean-air-mobility.com bikeradar.com masterflex.de alternative-energy-news.info ebiketestsieger.com hzwei.info cordis.europa.eu rssb.co.uk

Application	Source
Fuel cell electric scooters	gasworld.com hfcarchive.org intelligent-energy.com globalsuzuki.com actaspa.com fuelcellsworks.com archive.is centroestero.org hytetra.eu hzwei.info cordis.europa.eu fhshh.com ec.europa.eu therideadvice.com fronius.com

References

Data and Background Literature: Working Group 3 (1/3)

Application	Source
Fuel cell powered boats	businesswire.com hydrogenhouseproject.org energy-observer.org fronius.com fuelcellsworks.com itm-power.com gtr.rcuk.ac.uk ycsynergy.com cea.fr wired.co.uk theguardian.com boatinternational.com forseepower.com netinform.net

Application	Source
Fuel cell powered ships	powercell.se ship-technology.com gcaptain.com fairplay.ihs.com newenergy.is reuters.com charterworld.com boote-magazin.de nuvera.com fch.europa.eu

References

Data and Background Literature: Working Group 3 (2/3)

Application	Source
Fuel cell powered ferries	einnsyn.kystverket.no gasworld.com cmr.no fch.europa.eu sjofartsdir.no orkney.gov.uk heraldscotland.com ship-technology.com northsearegion.eu

Application	Source
Fuel cell powered aircrafts	dlr.de pipistrel.si fzt.haw-hamburg.de hycarus.eu cordis.europa.eu enfica-fc.polito.it

References

Data and Background Literature: Working Group 3 (3/3)

Application	Source
Fuel cell powered port operations equipment	greenport.com mynewsdesk.com hydrogencarsnow.com tts-i.com marketwired.com evworld.com fuelcellcars.com greencarcongress.com wired.com handyshippingguide.com porttechnology.org portofrotterdam.com

Application	Source
Fuel cell powered aircraft ground support equipment (GSE)	netinform.net mulag.de innovatek.com airport-suppliers.com hylift-europe.eu now-gmbh.de hydrogen.energy.gov jungheinrich.com

References

Data and Background Literature: Working Group 4 (1/4)

Application	Source
Fuel cell powered gen-sets	atrexenergy.com fch.europa.eu fuelcellsworks.com boconlineblog.co.uk

Application	Source
Fuel cell off-grid power	atrexenergy.com fch.europa.eu ec.europa.eu boconline.co.uk hydrogenics.com ballard.com

References

Data and Background Literature: Working Group 4 (2/4)

Application	Source
Fuel cell powered back-up system	atrexenergy.com plugpower.com dlr.de now-gmbh.de ballard-power.developmentwebsite.ca cordis.europa.eu 2020-horizon.com boconline.co.uk

Application	Source
Fuel cells for residential use	h2fc-fair.com bhkw-infothek.de bmvi.de enefield.eu hexis.com svgw.ch Galileo kesselheld.de youtube.com, Fraunhofer-Institut

References

Data and Background Literature: Working Group 4 (3/4)

Application	Source
Fuel cells in commercial buildings	fuelcellsworks.com hydrogen.energy.gov ieahydrogen.org betterbuildingspartnership.co.uk fuelcelltoday.com breeam.com

Application	Source
Fuel cells in industrial use cases	youtube.com, Fraunhofer-Institut energy.gov fch.europa.eu

References

Data and Background Literature: Working Group 4 (4/4)

Application	Source
Hydrogen-based district heating	hydrogenfuelnews.com koreaherald.com powertogas.info microgridknowledge.com utilitydive.com meks-energie.de eti-brandenburg.de enertrag.com eike-klima-energie.eu fuelcellenergy.com fch.europa.eu

References

Data and Background Literature: Working Group 5 (1/2)

Application	Source
Grid services	fch.europa.eu hydrogenics.com itm-power.com hygear.com h2b2.es industry.siemens.com siemens.com scandinavianhydrogen.org powertogas.info uniper.energy lbst.de iphe.net areva.com iea.org

Application	Source
Energy storage	sbcenergyinstitute.com areva.com uniper.energy ingridproject.eu mcphy.com itm-power.com don-quichote.eu fch.europa.eu globalislands.net iphe.net iea.org

References

Data and Background Literature: Working Group 5 (2/2)

Application	Source
Demand management	hydrogenics.com itm-power.com hygear.com h2b2.es industry.siemens.com fch.europa.eu cordis.europa.eu hpem2gas.eu engerati.com uniper.energy windgas-hamburg.com cedec.com szg-energiespeicher.de scandinavianhydrogen.org iea.org

Application	Source
Frequency response	hydrogenics.com sbcenergyinstitute.com itm-power.com hygear.com h2b2.es industry.siemens.com fch.europa.eu klimafonds.gv.at omv.com oekonews.at powertogas.info rh2-wka.de sotaventogalicia.com juser.fz-juelich.de statoil.com iphe.net scandinavianhydrogen.org iea.org

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