Fuel Cells and Hydrogen Applications for Regions and Cities Vol. 2

Cost analysis and high-level business case

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This compilation of application-specific information forms part of the study ***"Development of Business Cases for Fuel Cells and Hydrogen Applications for European Regions and Cities"*** commissioned by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2 JU), N° FCH/OP/contract 180, Reference Number FCH JU 2017 D4259 .

The study aims to **support a coalition of currently more than 90 European regions and cities** in their assessment of fuel cells and hydrogen applications to support project development. Roland Berger GmbH coordinated the study work of the coalition and provided analytical support.

All information provided within this document **is based on publically available sources** and reflects the **state of knowledge as of August 2017**.

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Summary of findings

Initially, we summarize a set of general conclusions and comparative results of the preliminary business case analysis

Objectives and underlying premises of comparing FCH applications

Main objectives

> **Help participating Regions and Cities navigate** the large pool of applications – in terms of key decision-making dimensions

> **Identify common challenges and opportunities** – to start discussions about integrated deployment approaches

> **Provide first orientation for individual strategic fit** assessment

> **Identify further areas for detailed analysis** in Phase 2

Key premises for comparing FCH applications

> **Time horizon:** focus on the next 2-3 years – a realistic deployment timeline following this project

> **Alternative technologies:** benchmark FCH applications against conventional and/or other 0-emission technologies

> **Markets:** focus on Europe as market environment, e.g. in terms of commercial availability and regulation

> **Use cases:** attempt to abstract from specific use cases and consider a "representative" deployment context (e.g. operators' requirements, fleets, energy prices) – regionalisation in Phase 2

> **Financing:** exclude any specific public support schemes in the initial, general analyses

Source: FCH2 JU, Roland Berger

The FCH applications in scope are heterogeneous – Different tech. readiness, economic competitiveness and deployment complexity

Evaluation of 10 FCH applications[1] across seven dimensions

INDICATIVE

		1 TRL	2 Economic competitiveness	3 Environmental benefits	4 Unique selling propos.	5 Ease of deployment	6 Direct procurement	7 Visibility as "showcase"
Transport applications	(Urban) Buses	■	▨	■	■	▨	■	■
	Cars	■	▨	■	■	■	▨	■
	Delivery vans	▨	□	■	▨	▨	□	■
	Heavy-duty trucks	▨	□	■	▨	▨	□	■
	Trains	▨	■	■	■	▨	▨	■
	Port operations	□	▨	■	▨	□	□	□
Stationary applications	Power to H_2	■	▨	▨	■	□	▨	□
	H_2 injection into gas grid	■	□	▨	■	□	▨	□
	Residential mCHP	■	▨	▨	▨	■	▨	▨
	Off-grid power	■	□	■	■	▨	▨	▨

■ High ▨ Medium □ Low

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1) Please note that the selection only contains the ten top-ranked applications as stated by the Regions and Cities in the initial self-assessment survey (June 2017)
2) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration

Source: FCH2 JU, Roland Berger

TRL range from 4 to 9 – Forklift trucks, cars and mCHPs have the highest TRL; they are fully commercially available

TRL and commercial availability compared to alternative technologies[1]

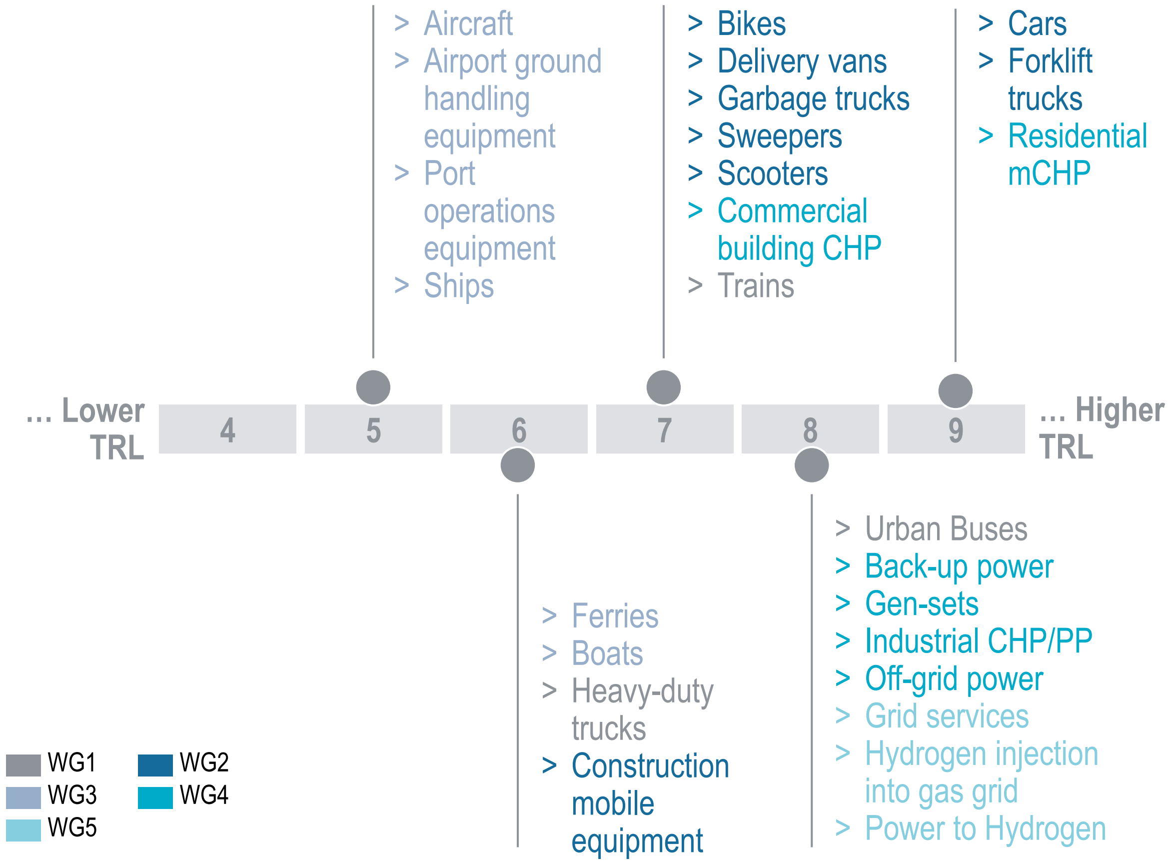
INDICATIVE

Key question

To what extent is the FCH application **technologically mature** and can be considered **commercially available** in Europe compared to competing technologies?

Key metrics

- Technology Readiness Level (TRL)
- Industrial capacities
- Deployable volumes
- …



5:
- Aircraft
- Airport ground handling equipment
- Port operations equipment
- Ships

6:
- Ferries
- Boats
- Heavy-duty trucks
- Construction mobile equipment

7:
- Bikes
- Delivery vans
- Garbage trucks
- Sweepers
- Scooters
- Commercial building CHP
- Trains

8:
- Urban Buses
- Back-up power
- Gen-sets
- Industrial CHP/PP
- Off-grid power
- Grid services
- Hydrogen injection into gas grid
- Power to Hydrogen

9:
- Cars
- Forklift trucks
- Residential mCHP

---

1) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration

Source: FCH2 JU, Roland Berger

Forklift trucks are among the few applications that can build a business cases on a stand-alone basis; trains are not far behind

Economic competitiveness compared to technologies[1]

INDICATIVE

Key question

How **economically competitive** is the FCH application from the user's/operator's perspective compared to key (0-emission or conventional) competitors?

Key metrics

- Total cost of ownership (TCO), levelized cost of energy (dep. on typical economic decision making process)
- Estimated cost of system / purchase price
- Cost premium
- ...

Low

Significant cost premium for FCH application [generally >100% TCO][2]

- Heavy-duty trucks [+10-200%]
- Construction mobile equipment
- Delivery vans [+100-400%]
- Scooters
- Ships
- Aircraft
- Back-up power
- Comm. CHP [100-300%]
- Gen-sets
- Off-grid power

Medium

Moderate cost premium for FCH application [generally 30-100% TCO]

- Cars [+80-100%]
- Garbage trucks [+30-50%]
- Sweepers
- Urban buses [+60-80%]
- Airport ground equ.
- Boats
- Ferries [+40-60%]
- Port op's equipment
- Ind. CHP/PP [-30-200%]
- Res. mCHP [30-60%]
- Power to H_2 [-10-400%]
- Grid services (add-on)
- H_2 injection into gas grid (add-on)

High

Small or even no cost premium for FCH app. [generally <30% TCO]

- Bikes
- Forklift trucks [-5-15%]
- Trains [+10-20%]

■ WG1 ■ WG2
■ WG3 ■ WG4
■ WG5

Economic competitiveness

---

1) Results differ depending on time horizon (here short-term horizon of next 2-3 years, excl. public support schemes), benchmark as well as specific use case

2) Values in parentheses "[ ]" are based on results of the prel. business case anylsis; they indicate the relative TCO premium of the FCH application over the conventional benchmark

Source: FCH2 JU, Roland Berger

Environmental benefits differ, e.g. dep. on efficiency, fuel, size/scale of typical deployments and technologies that are replaced

Environmental benefits compared to competing technologies[1]

INDICATIVE

Key question

How significant are the **environmental benefits[2]** of a an FCH application in a typical use case / deployment compared to the main (conventional) competing technologies, considering both relative emissions savings and absolute abatement (e.g. vehicle fuel consumption, fleet sizes)?

Key metrics

> Greenhouse gas emission savings (especially CO_2)
> Pollutant emission savings (especially NO_x)
> Noise emission savings

Moderate
Relatively moderate environmental benefits

> Bikes
> Construction mobile equipment
> Garbage trucks [25-35%][3]
> Scooters
> Sweepers
> Gen-sets
> Airport ground handling equipment

Significant
Significant environmental benefits

> Forklift trucks [n/a]
> Boats
> Back-up power
> Comm. CHP [5-35%]
> Ind. CHP/PP [5-65%]
> Res. mCHP [10-50%]

Very strong
Very strong environmental benefits

> Cars [30-40%]
> Delivery vans [15-75%]
> Heavy-duty trucks [20-30%]
> Urban buses [20-30%]
> Trains [15-25%]
> Aircraft
> Ferries [15-30%]
> Port op's equipment
> Ships [25-35%]
> Off-grid power [-20-30%]
> Power to Hydrogen
> Grid services
> Hydrogen into gas grid

Please note: All hydrogen-fuelled FCH applications have zero local (TTW) emissions. When considering green hydrogen as medium-long term hydrogen supply options , local (TTW) and total (WTW) emissions fall to zero for all applications.

■ WG1 ■ WG2
■ WG3 ■ WG4
■ WG5

Environmental benefits

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1) Results differ depending on time horizon (here short-term horizon of next 2-3 years, benchmark as well as specific use case
2) This indication is based on a typical use case for FCH applications, considering emissions savings of a typical use case (single unit or fleet), based on cons. of "grey" hydrogen
3) Values in parentheses "[ ]" are based on results from the prel. business case analysis and indicate the potential CO_2 emission savings compared to conventional (fossil-fuel) technologies

Source: FCH2 JU, Roland Berger

Several applications, e.g. forklifts, trains and buses, have already found a clear USP and focus on specific use cases

Unique Selling Proposition (USP) compared to alternative technologies[1]

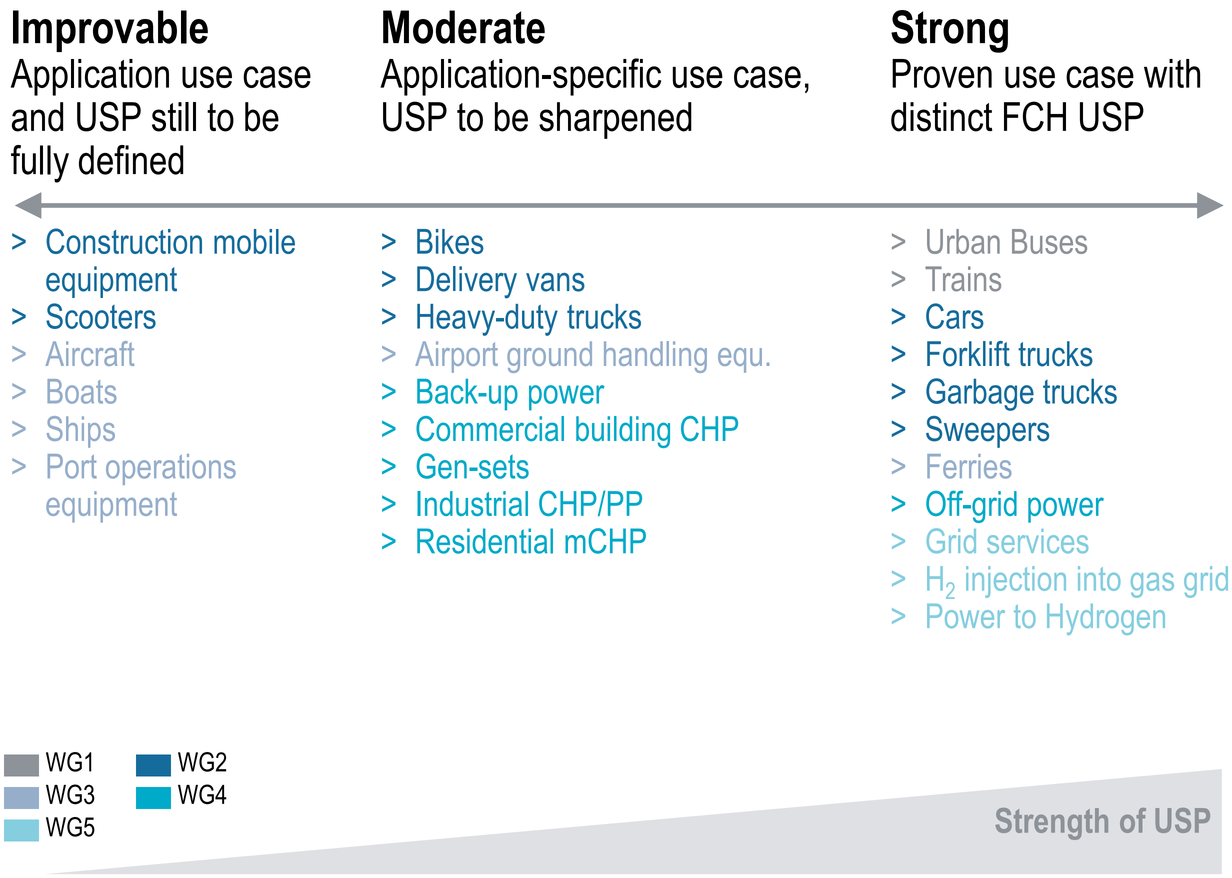
INDICATIVE

Key question

Does the FCH application have a **unique selling proposition** (e.g. refuelling time, range, use case fit) compared to other low or zero emission technologies – from a user`s/operator`s point of view?

Key metrics

- Proven, tailored, viable use case
- Operational advantages
- New business models / opportunities
- Regulatory incentives
- …



Improvable
Application use case and USP still to be fully defined

- Construction mobile equipment
- Scooters
- Aircraft
- Boats
- Ships
- Port operations equipment

Moderate
Application-specific use case, USP to be sharpened

- Bikes
- Delivery vans
- Heavy-duty trucks
- Airport ground handling equ.
- Back-up power
- Commercial building CHP
- Gen-sets
- Industrial CHP/PP
- Residential mCHP

Strong
Proven use case with distinct FCH USP

- Urban Buses
- Trains
- Cars
- Forklift trucks
- Garbage trucks
- Sweepers
- Ferries
- Off-grid power
- Grid services
- H_2 injection into gas grid
- Power to Hydrogen

■ WG1
■ WG2
■ WG3
■ WG4
■ WG5

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1) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration

Source: FCH2 JU, Roland Berger

Implementation-related ease of deployment differs and depends e.g. on infrastructure requirements and necessary stakeholder buy-in

Implementation-related ease of deployment

INDICATIVE

Key question

How **easy** is the implementation of the application in comparison to competing technologies? Or in other terms – how complex is it?

Key metrics

- Setup time and cost
- Infrastructure requirements
- Number of stakeholders to be involved per project
- Project management requirements
- Completeness of FCH regulation
- Workforce training requirements

Low
Relatively complex deployment

- Aircrafts
- Port operations equipment
- Ships
- Back-up power
- Grid-services
- Hydrogen injection into gas grid
- Power to Hydrogen

Medium
Moderate complexity

- Heavy-duty trucks
- Trains
- Urban buses
- Cars
- Construction mobile equ.
- Delivery vans
- Garbage trucks
- Scooters
- Sweepers
- Airport ground handling equ.
- Ferries
- Off-grid power

High
Straightforward implementation

- Bikes
- Forklifts
- Boats
- Commercial CHP
- Gen-sets
- Industrial CHP/PP
- Residential mCHP

■ WG1
■ WG2
■ WG3
■ WG4
■ WG5

Ease of deployment

1) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration

Source: FCH2 JU, Roland Berger

Regions & cities have several options to engage directly in the deployment of FCH applications, e.g. in public transportation

Potential for Regions & Cities to act as direct customers, operators, etc.[1]

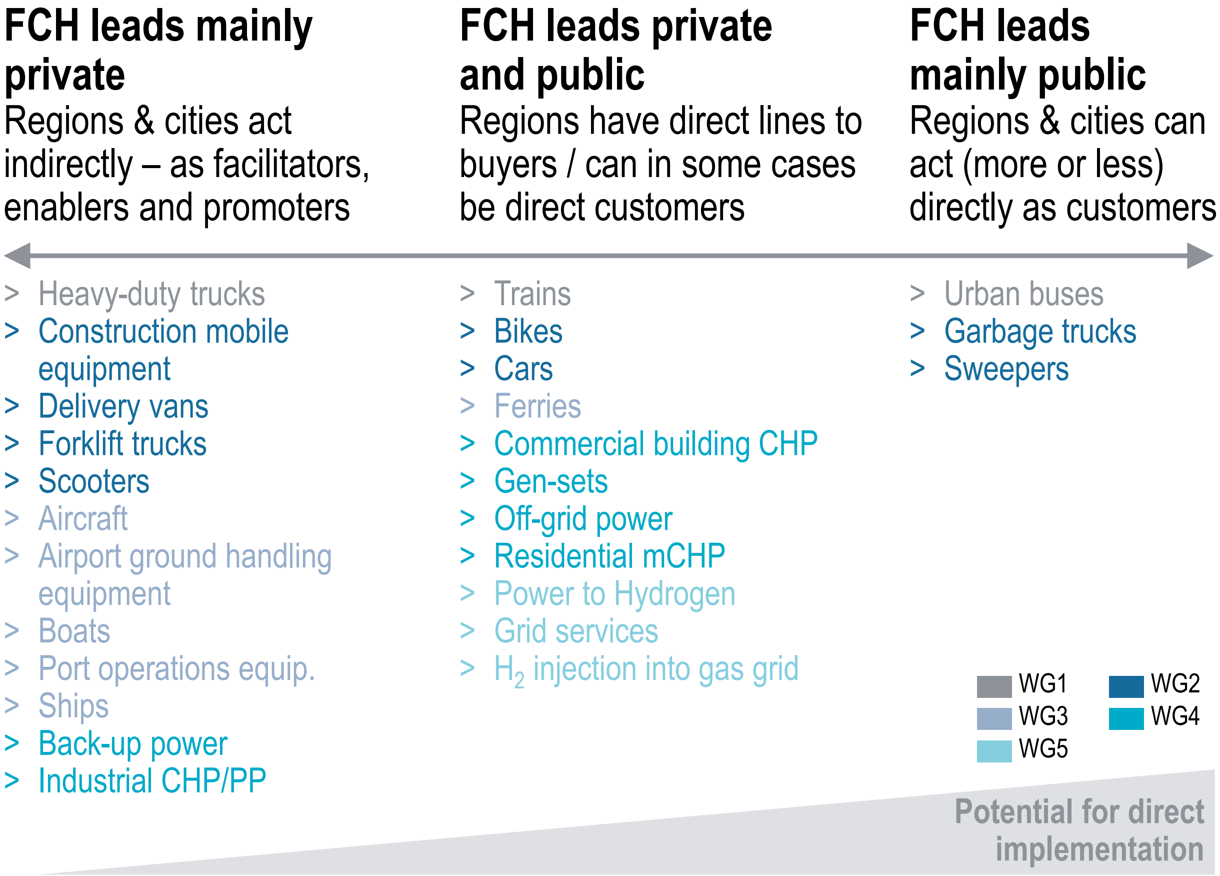
INDICATIVE

Key question

How are the possibilities for regions and cities to **implement** FCH applications as users/operators? Do they act as direct customers or are they rather indirect facilitators/enablers for private users?

Key metrics

- Owner of technology purchasing decision (public vs. private)
- Common operating model
- Potential of regions and cities as multiplier/facilitator
- …



FCH leads mainly private
Regions & cities act indirectly – as facilitators, enablers and promoters

- Heavy-duty trucks
- Construction mobile equipment
- Delivery vans
- Forklift trucks
- Scooters
- Aircraft
- Airport ground handling equipment
- Boats
- Port operations equip.
- Ships
- Back-up power
- Industrial CHP/PP

FCH leads private and public
Regions have direct lines to buyers / can in some cases be direct customers

- Trains
- Bikes
- Cars
- Ferries
- Commercial building CHP
- Gen-sets
- Off-grid power
- Residential mCHP
- Power to Hydrogen
- Grid services
- H_2 injection into gas grid

FCH leads mainly public
Regions & cities can act (more or less) directly as customers

- Urban buses
- Garbage trucks
- Sweepers

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1) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration

Source: FCH2 JU, Roland Berger

Public transport applications are particularly visible to the public and hence have a great potential to act as FCH "showcases"

Visibility as public "showcase" to promote overall FCH technology[1]

INDICATIVE

Key question:

How **visible** is the application in the every day life of European citizens? How large is its impact in promoting the acceptance of fuel cell and hydrogen technologies?

Key metrics:

- Degree of usage in public space and by European citizens
- Role in public infrastructure provision
- Location and size of application
- …

Limited
Relatively limited visibility

- Forklift trucks
- Airport ground handling equipment
- Port operations equipment
- Ships
- Industrial CHP/PP
- Grid services
- Hydrogen injection into gas grid
- Power to Hydrogen

Moderate
Moderate public visibility

- Construction mobile equipment
- Aircraft
- Boats
- Back-up power
- Comm. building CHP
- Gen-sets
- Off-grid power
- Residential mCHP

Strong
Strong public visibility

- Heavy-duty trucks
- Trains
- Urban buses
- Bikes
- Cars
- Delivery vans
- Garbage trucks
- Scooters
- Sweepers
- Ferries

■ WG1
■ WG2
■ WG3
■ WG4
■ WG5

Visibility

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1) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration

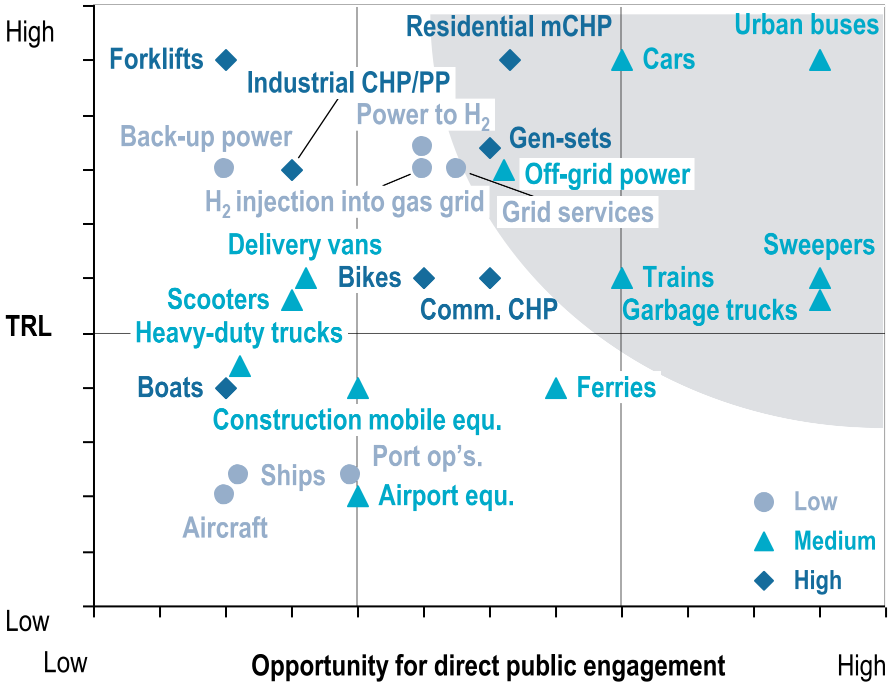
Source: FCH2 JU, Roland Berger

Some applications can be deployed in the short term, as they are comm. available and implementation lies within in the public domain

Short-term deployment opportunities for Regions and Cities

INDICATIVE

What applications can I deploy tomorrow?



Implementation-rel. ease of deployment:

Key considerations

- In the short term, Cities and Regions can look for **high TRL applications** for actual deployment projects
- **Public infrastructure sectors** are well suited for deployment of applications because of direct control of public authorities (e.g. publically-owned local/regional transport operators or utilities)
- Cities and Regions can reduce complexity in multi-stakeholder settings by acting as **direct customers** of industry

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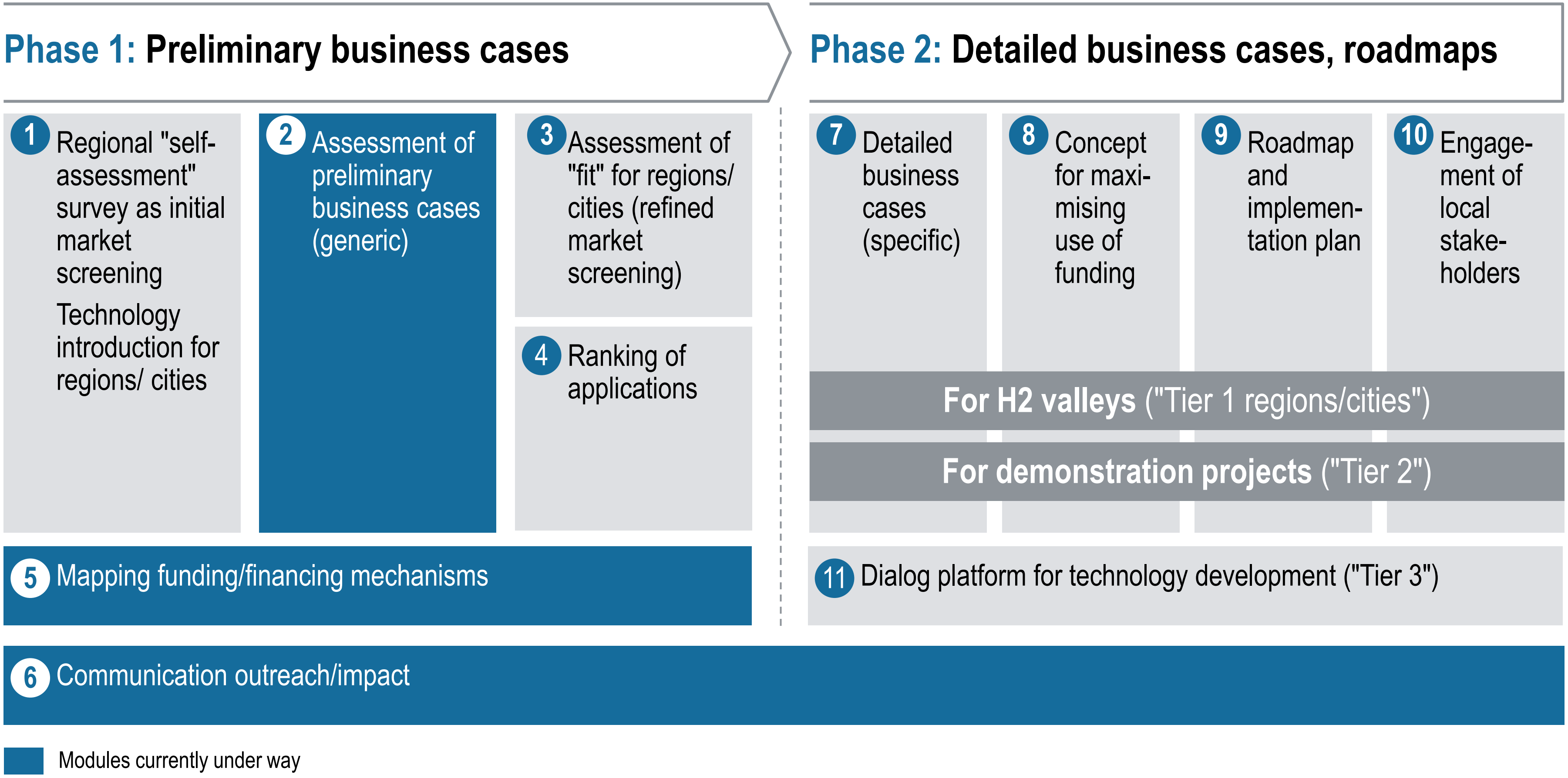
1) Results differ depending on location, time horizon, benchmark technology as well as specific use case under consideration
2) Applications in parentheses are still to be discussed within Working Group Calls
Source: FCH2 JU, FCH2 JU, Roland Berger

Going forward, the preliminary business case analyses are the basis for the renewed assessment of all applications by Regions & Cities

Recap. of project approach: two phases and eleven modules



Phase 1: Preliminary business cases

1 Regional "self-assessment" survey as initial market screening

Technology introduction for regions/ cities

2 Assessment of preliminary business cases (generic)

3 Assessment of "fit" for regions/ cities (refined market screening)

4 Ranking of applications

5 Mapping funding/financing mechanisms

Phase 2: Detailed business cases, roadmaps

7 Detailed business cases (specific)

8 Concept for maximising use of funding

9 Roadmap and implementation plan

10 Engagement of local stakeholders

For H2 valleys ("Tier 1 regions/cities")

For demonstration projects ("Tier 2")

11 Dialog platform for technology development ("Tier 3")

6 Communication outreach/impact

■ Modules currently under way

Source: FCH2 JU, Roland Berger

A. WG1: "Heavy duty transport applications"

Working Group 1 has attracted interest from a broad coalition of Regions and Cities as well as industry players

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

BOC
Air Liquide
SERA consulting
CALVERA Hydrogen
BALLARD
BMW GROUP
ITM POWER
VDL BUS & COACH
TOYOTA
Nedstack
DAIMLER
HYDROGENICS
EvoBus
ALSTOM
H2B2
Symbio
PLUG POWER
THE LINDE GROUP
uniper
HOLTHAUSEN GROEP

Source: FCH2 JU, Roland Berger

Each analysis consist of 3 key elements (use case, technologies, performance) – Regional differences will be tackled in Phase 2

Prel. business case components and flow of analysis – SCHEMATIC

Exogenous assumptions, e.g. energy/fuel cost, carbon intensities

FCH application

- > Technical features (e.g. output, efficiency, lifetime, fuelling requirements) and general readiness
- > Est. CAPEX / system cost
- > Est. OPEX (e.g. maintenance)

… plus benchmarking against competing technologies

1 "generic" use case

…consisting of typical deployment requirements of European regions and cities

Basic performance

- Technical / operational
- Economic
- Environmental

Source: FCH2 JU, Roland Berger

A.1 Trains

Use case and applications determine capital, fuel, O&M and infrastructure cost that in turn make up the operator's TCO

Key elements of FCH transport applications' TCO – SCHEMATIC, SIMPLIFIED

Operator's perspective …

The task / scenario at hand: use case, deployment context, target operating model, e.g.

- Route definition and length, required stops/stations
- Target capacity
- Target roundtrip-time, target schedule for operations
- Target availability
- Topographic and other ext. conditions
- Fleet size, depot structure
- Energy cost
- Carbon intensities
- …

FCH train / system specifications and performance

- Size, volume, weight, other physical train configurations
- Maximum / average speed
- Powertrain design, i.e. fuel cell + battery + engine
- Fuel cell technology
- Efficiency / fuel consumption
- Hydrogen storage system
- Degradation
- Lifetime
- Availability
- …

Hydrogen infrastructure specifications and performance – sharing ratios

1. Capital cost

- Investment / depreciation
- Financing cost

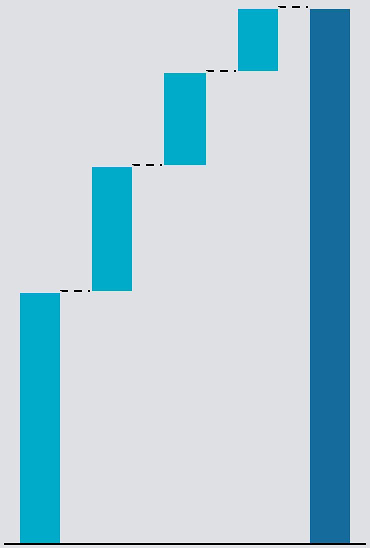
2. Fuel cost – H_2 consumption, H_2 price (dep. on production, distribution, volumes, input prices, etc.)

3. Other O&M cost, e.g. for train maintenance, personnel, utilities, fees/levies, taxes[1]

4. Infrastructure cost

- Investment / depreciation
- O&M cost

"Total Cost of Ownership" (TCO) in EUR p.a. or EUR/km



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[1] Largely excluded for preliminary business case analysis, more detailed consideration in Project Phase 2

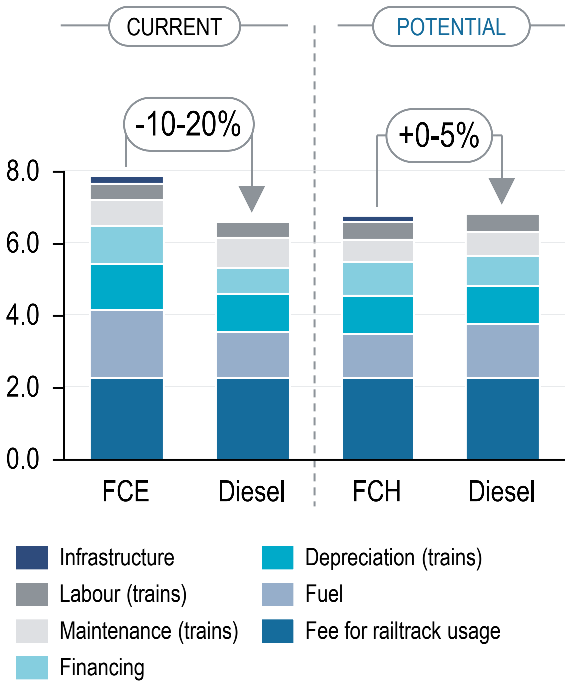
Source: FCH2 JU, Roland Berger

Hydrails might almost reach cost parity with diesel trains in the medium run, while reducing CO_2 and putting NO_x emissions to 0

Business case and performance overview – INDICATIVE EXAMPLE

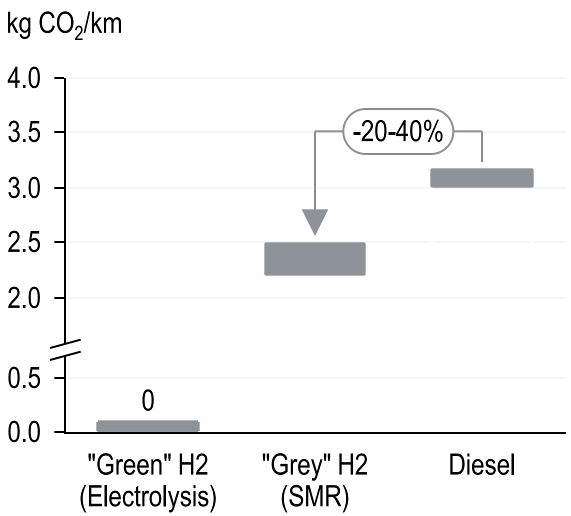
Economic

Estimated annualised Total Cost of Ownership (TCO) [EUR/km], 2017 prices



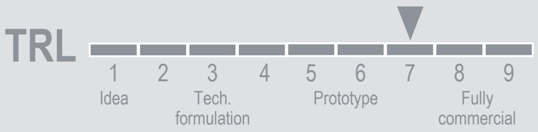
Environmental

- Zero tailpipe emissions of CO_2, pollutants such as NO_X and fine dust particles, e.g. saving ~15-25 t NO_X/year
- Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption)



Technical/operational

- Rising technical maturity of larger-scale fuel cell modules to be used in trains or tram cars; roll-out in Germany in first major "real-life" projects under way, tech. moving towards commercialisation for trains starting operations over the medium term (tender processes in part already ongoing)
- Once deployed, Hydrail OEMs would (feel compelled to) guarantee same availabilities of conventional diesel trains (e.g. approx. 97%), not withstanding initial deployment challenges
- Range of a fully fuelled Hydrail at 600-800 km, aiming to reach parity with diesel at up to 1,000 km



Source: FCH2 JU, Roland Berger

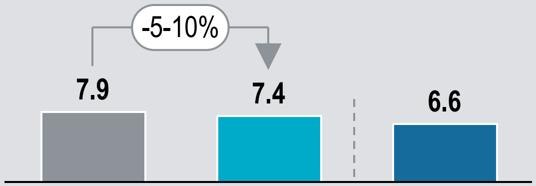
The impact of TCO-drivers varies, creating several levers for further reduction of hydrogen TCO compared to diesel TCO

Key determinants of the business case[1] – INDICATIVE EXAMPLE

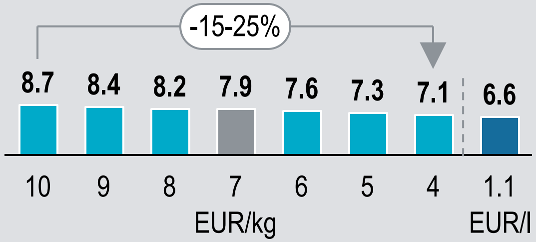
Important sensitivities considered …

… est. impact on TCO [EUR/km]

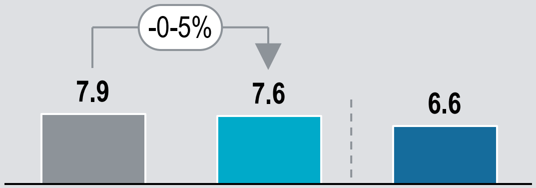
1 **Hydrail purchasing price:** reducing the purchasing price of the FCH train to the price of diesel trains in 2017 potentially results in the overall reduction of costs per km of EUR ~50 ct



2 **Fuel costs:** a price reduction for hydrogen to 4 EUR / kg H_2 potentially results in a reduction of EUR ~80 ct **– strong regional differences**



3 **Infrastructure costs:** omitting the infrastructure expenditures and therefore levelling the infrastructure related CAPEX-costs with the diesel case, potentially results in a cost reduction per km of EUR ~30 ct **– strongly dependent on fleet size and depot structure**



■ Hydrail TCO, base case ■ Hydrail TCO, adjusted variables ■ Diesel train TCO, base case

1) Unless otherwise stated, all statements shall be considered as 2017-based and *ceteris paribus*, i.e. "all-other-things-equal"

Source: FCH2 JU, Roland Berger

As an example, we considered a relatively sizeable fleet deployment of Hydrails, with changing cost and performance parameters

Key assumptions – INDICATIVE EXAMPLE

Application-related assumptions

today / outlook	**Hydrail**	**Diesel train**
Technical specifications	150 passenger (seated) Lifetime: 15 years Availability: 95% / *97%*	150 passenger (seated) Lifetime: 15 years Availability: 97% / *97%*
CAPEX		
> Price train [unit]	EUR 5-5.5 m / *4.5[1] m*	EUR 4-4.3 m / *4.5 m*
> Initial HRS[2]	EUR 9 m / *7.2 m*	-
Fuel		
> Fuel type	Hydrogen (350 bar)	Diesel
> Consumption	0.28 / 0.25 kg H_2 / km	*1.2 / 1.4* l diesel / km
Maintenance costs		
> Train per km	EUR 0.72 / *0.65*	EUR 0.79 / *0.71*
> Ref. station p.a.	EUR 180k / *180k*	EUR 10,350 / *10,350*
Labour costs p.a.	EUR 128,000 / *128,000*	EUR 128,000 / *128,000*

Use case and exogenous factors

Strongly dependent on reg. circumstances

- > The assumed train operator has several non-electrified routes of ~100 km and ~10 stops each to service. The trains travel at an average speed of ca. 80 km/h. The ambition is to service the route during peak hours hourly, with 10 hours in operation + additional refuelling time per day. The operator deploys ~15 trains with a total expected distance travelled by each train of ~750 km per day (fleet travels ~4 m km per year)
- > Hydrogen consumption: ~230-260 kg/d (1 train), ~3,450-4,000 kg/d (fleet)
- > Financing costs of train operator: 5% p.a.
- > Labour costs: based on 2 shifts and 4 FTE per train, with average Western European wages of EUR 32,000 per person per year
- > CAPEX for refuelling stations: one HRS at central depot for FCH trains; for counterfactual diesel train deployment no additional investment considered due to wide-spread availability of diesel refuelling infrastructure today

Strongly dependent on reg. circumstances

- > Source of hydrogen: Steam-Methane Reforming (SMR), truck-in
- > Cost of hydrogen for operator: 7 EUR/kg H_2 / *5* EUR/kg H_2
- > Cost of diesel : 1.1 EUR/litre / *1.25* EUR/l
- > CO_2 emissions from grey hydrogen: 9 kg / kg H_2
- > CO_2 emissions from green hydrogen: 0 kg / kg H_2
- > CO_2 emissions from diesel: 2.64 kg/l
- > NO_x emissions from diesel: 4 g/l

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1) Assuming production-at-scale scenarios for Hydrail OEMs, current price of diesel train as initial target price for Hydrail (preliminary – to be validated)

2) HRS cost preliminary – to be validated

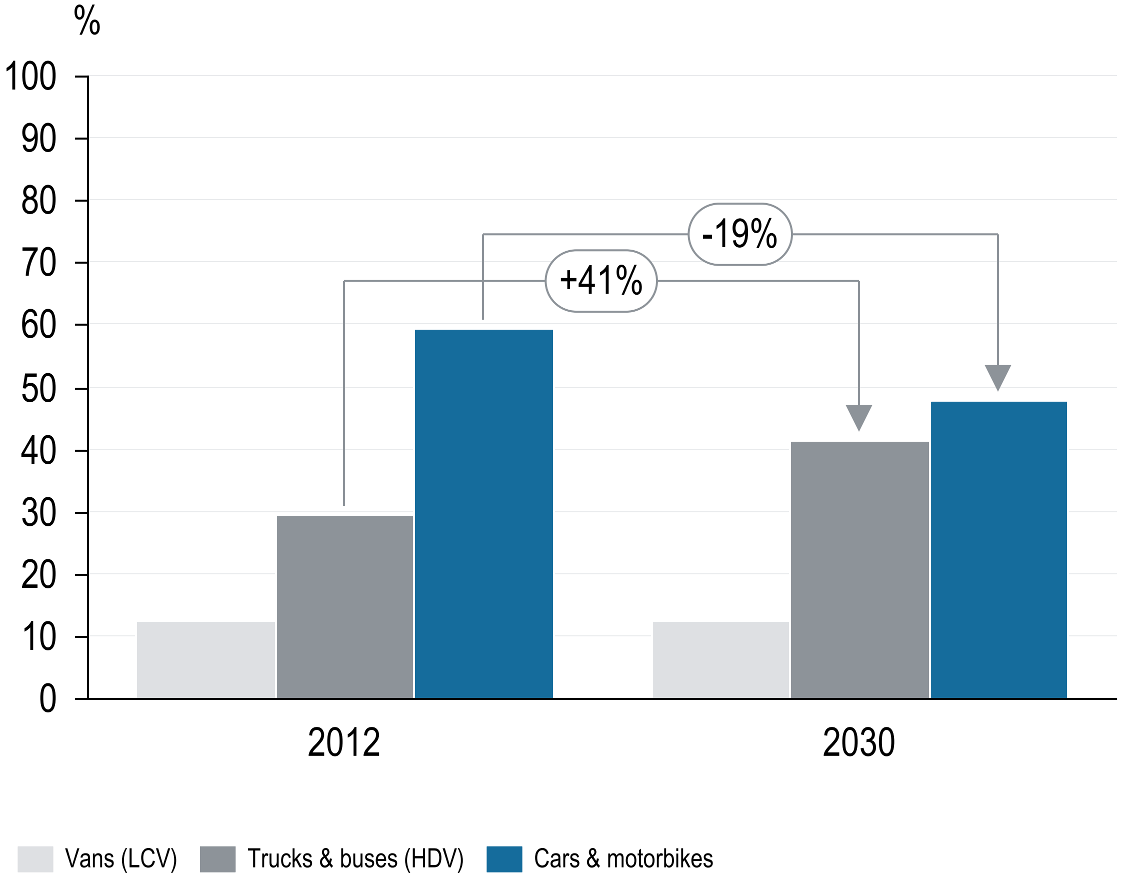
Source: FCH2 JU, NOW, Roland Berger

A.2 Heavy-duty trucks

Giving their growing share in road transport GHG emissions, future European regulation will likely also tackle heavy-duty trucks

European road transport greenhouse gas (GHG) emissions [%]

INDICATIVE



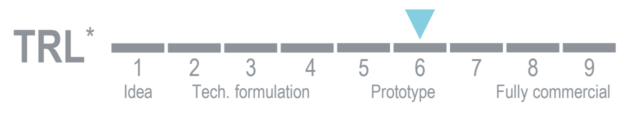
- **Emissions from heavy-duty vehicles (HDV), incl. trucks, grew by >35% from 1990 to 2010** and keep increasing. Without additional measures, they are projected to reach as much as 40% of European road transport emissions by 2030
- Current emission regulations in road transport focuses heavily on passenger cars; **it is to be expected that future regulation will tackle trucks as well** – even considering that efficiencies have already been maximised to a great extent, given the highly commercial nature of the sector and the high share of fuel cost in total cost of ownership
- **Several levers for further reducing truck emissions exist** – for example from:
  - Alternative powertrains (e.g. fuel cells)
  - Alternative fuels (e.g. hydrogen)
  - Other levers, e.g. digitization effects such autonomous driving

Source: Transport Environment, EEA, European Commission, FCH2 JU, Roland Berger

First truck prototypes with FCH powertrains are being deployed – Commercial availability of vehicles is expected to improve

Status of fuel cell electric heavy-duty trucks

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: FCH2 JU, Roland Berger

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

[1]) Specifically adjusted to port requirements

The truck market is highly heterogeneous with respect to use cases as well as available (and conceivable) low/0-emission technologies

Trucks by category and available low/0-emission technologies

Classification[1]	< 3.5 t	> 3.5 t; < 7.5 t	> 7.5 t; < 12 t	> 12 t	Truck tractor
Description – Use case	Typical "Sprinter" delivery vans, e.g. "last mile" parcel delivery	Delivery in short distance traffic, e.g. around central distribution centre (typically light goods; inner cities)	Delivery in regional transport, transport of bulky goods, e.g. around regional distribution centre	Motor vehicle for drawbar trailer in long-distance hauling, on-site traffic, e.g. for transport companies with standardized freight	Long-distance hauling, e.g. for international transport or transport of goods with special storage requirements
Range [avg. yearly range]		12,300 – 13,700 km	25,700 – 28,400 km	70,300 – 77,700 km	101,000 – 111,000 km
Emissions[2]		~ 430 g/km	~ 590 g/km	~ 780 g/km	~ 1,000 g/km
Low/0-emission technologies		FCEV, FC hybrid, BEV, CNG/LNG, Diesel[3]	FCEV, FC hybrid, BEV, CNG/LNG, Diesel[3]	FCEV, FC hybrid, BEV, CNG/LNG, Diesel[3]	FCEV, FC hybrid, CNG/LNG, Diesel[3]
Engine output **Consumption**		Highly dependent on individual use case, for example type of good transported, truck superstructure, etc.; trend towards heavily over motorized fleet			

PLEASE SEE WG 2

1) Gross vehicle weight 2) Well-to-Wheel CO2 emissions for all street categories assuming Euro-IV diesel powertrain and 50% utilization 3) Overhead lines with diesel hybrid trucks

Source: Gnann et al. 2017; DLR, Shell, HWWI 2010; FCH2 JU, Roland Berger

Alternative powertrains still face several challenges, especially regarding the economics of regional and long-distance hauling

Powertrain benchmarking, segment ">12 t" (typ. up to 24-26 t)

INDICATIVE

		1 FCH Truck	2 Diesel truck	3 CNG/LNG truck	4 BE truck
CAPEX [EUR]	**Actual 2015**	302,000-334,000	62,000-68,000	95,000-105,000	175,000-193,858
	Estimate 2030	115,000-127,000	78,000-86,000	136,000-150,000	124,000-137,000
Consumption [kWh/km]	**Actual 2015**	1.91-2.11	2.27-2.51	2.53-2.79	1.04-1.14
	Estimate 2030	1.64-1.82	1.80-1.98	2.03-2.25	0.91-1.01
Maintenance [EUR/km]	**Actual 2015**	0.48-0.53	0.15-0.16	0.17-0.19	0.24-0.27
	Estimate 2030	0.11-0.12	0.15-0.16	0.15-0.16	0.11-0.12
Range[1)]		Medium-high range ◕	High range ●	Medium-high range ◑	Low-medium range[2] ◔
Lifetime		Typical holding periods are ~6 years (e.g. with ~100k km p.a.). Proxy considerations look diesel/FC buses to draw conclusions for FC trucks. Typically, bus demo. projects have shown the two technologies at par.			
Key challenges		Availability of infrastructure; trade-off between size of hydrogen tanks (range) and cargo payload; vehicle cost	CO_2 and NO_x emissions and related regulation	Infrastructure availability/range limitation, higher upfront CAPEX investment	Cost, size and weight of batteries; range limitations; extended recharging times
TRL level		Level 6 - 7	Level 9	Level 8 - 9	Level 6 - 7

1) Expected, still being tested and under constant development
2) BEVs' operational ability to service this segment questionable (different considerations for long-haul logistics vs. depot-based regional distribution use cases)

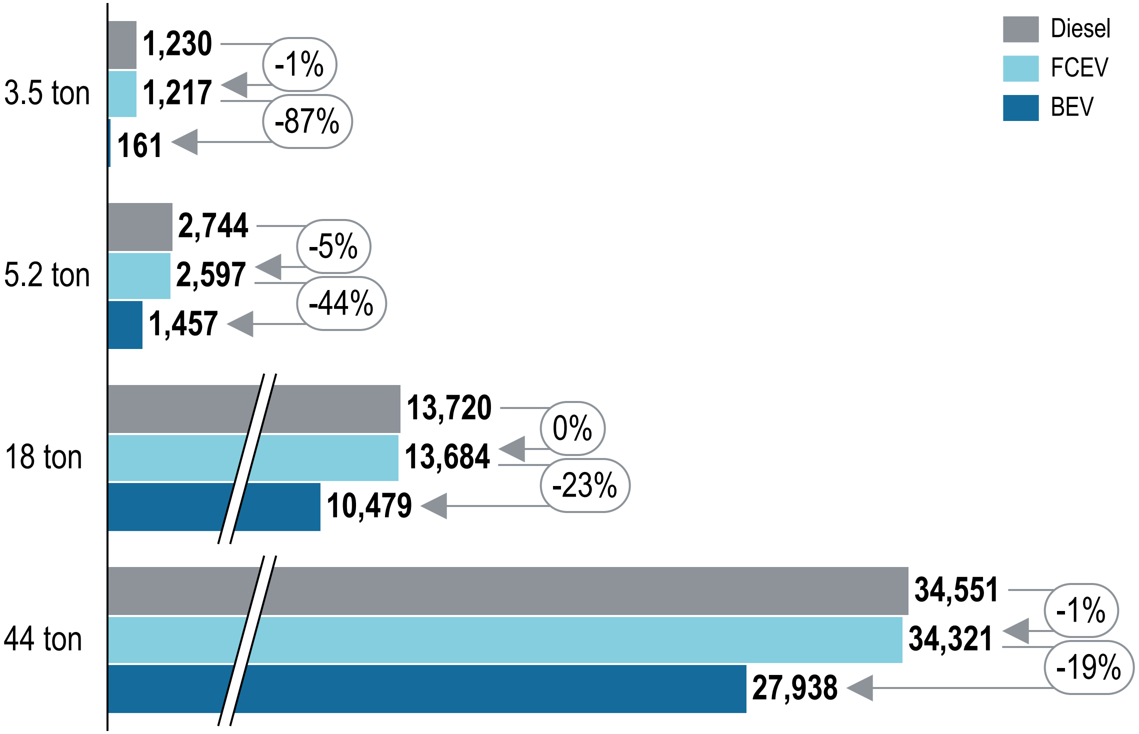
Source: Gnann et al. 2017, FCH2 JU, Roland Berger

In principle, analysts see FCH as a viable option for 0-emission heavy-duty/long-haul trucking – esp. from a payload perspective

Trade-off between alternative powertrains and payload acc. to US DOE

Payload benchmark of alternative powertrains

Available payload for different truck categories and powertrains [kg]



Trade-off considerations

- Assumption: payload considered at **800 km driving range**
- Fuel cell trucks only compromise up to 5% of the payload of the incumbent diesel technology
- BEV trucks offer between 19 and 87% less available cargo payload
- Please note:
  - 800 km driving range is at the upper limit of feasible mileage per day
  - Currently available batteries are economically not fit to match a 800 km driving range. Size and weight of necessary units are show stoppers

Key take-away

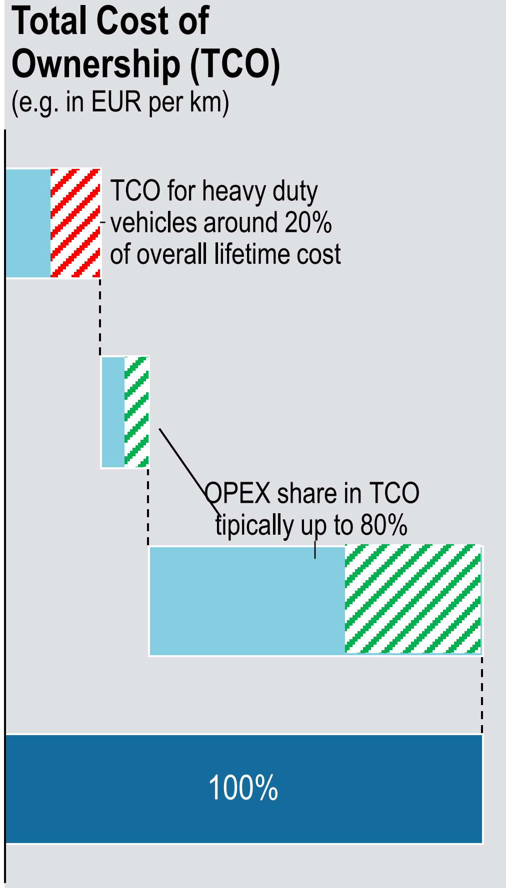
FCEV trucks are an attractive option to replace regional and long distance diesel trucks – from an payload point of view

Source: US Department Of Energy - Medium and Heavy Duty Fuel Cell Electric Truck Targets (2016), FCH2 JU, Roland Berger

FC trucks need significant OPEX savings in order to compete against other low/0-emission competitors

Schematic TCO comparison of different FC trucks – SIMPLIFIED

INDICATIVE



	1. Fuel cell	2. Diesel	3. CNG/LNG	4. Battery[1]
Capital cost	> Higher cost/kW > Higher development and permitting cost	> Lower cost/kW > Maturity level reached, low development cost	> Lower cost/kW > Production-at-scale nearly reached	> Higher cost/kW > Higher cost for reaching adequate range (if tech. possible)
Ops. & Maint.	> Less frequent routine, lower cost	> Higher maintenance cost due to engine set-up	> Higher maintenance frequency for safety reasons	> Higher maintenance cost with decr. battery performance
Fuel cost	> Lower fuel prices (with H_2 supply onsite) > High efficiency	> Highly regulated & uncertain prices > Lower efficiencies	> Price-sensitive fuel segment > Lower efficiencies	> Lower fuel prices, but many recharging cycles > High efficiency

Take-away

The upfront investment weights relatively little when considering the intense use and yearly km driven by the trucks; OPEX (esp. fuel cost) become the relevant differentiating factors

▨ Additional **cost** range for alternative powertrains ▨ Range for additional **savings** through alternative powertrains

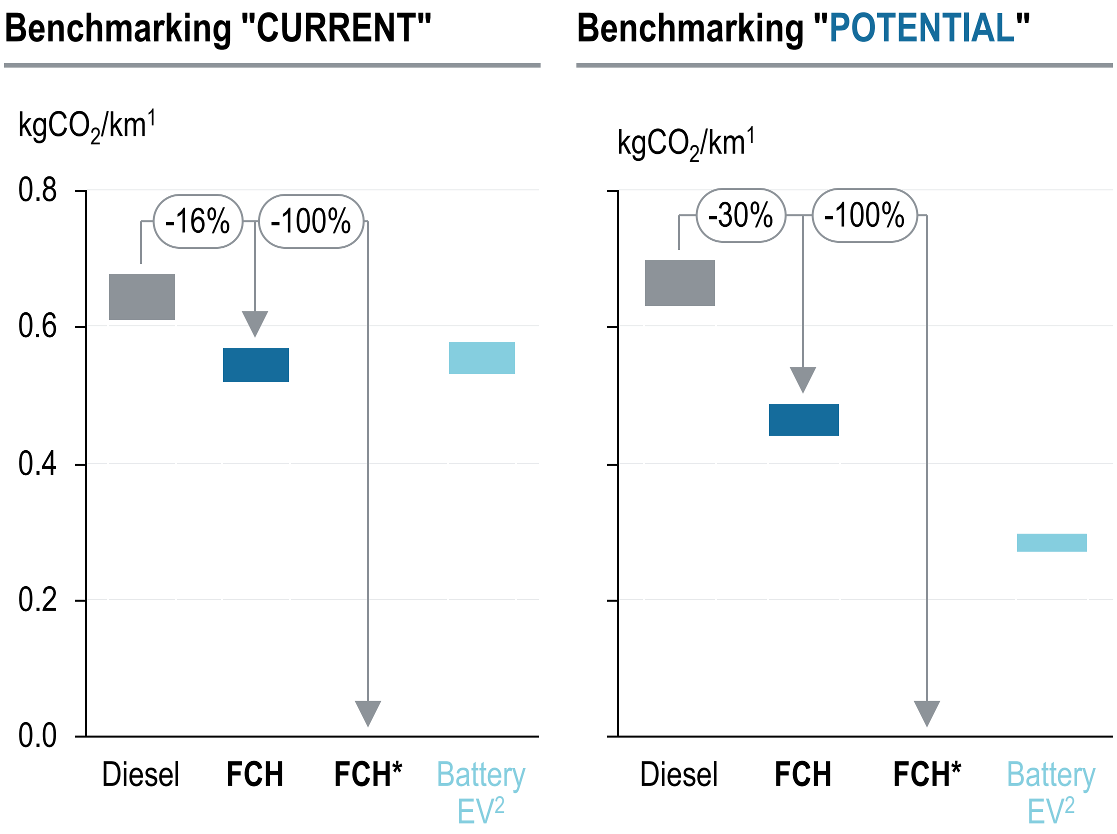
Source: FCH2 JU, Roland Berger

1) BEVs' operational ability to service key truck segments questionable (different considerations for long-haul logistics vs. depot-based regional distribution use cases)

FC trucks are the "cleanest" option amongst the fully flexible competing technologies; green H_2 bears 0-WTW-emission potential

WTW emissions benchmarking, segment ">12 t" (typ. up to 24-26 t)

INDICATIVE



- > **Key drivers**:
  - – Availability of green hydrogen is decisive in outperforming the benchmark technologies
  - – Development of the energy mix highly determines the environmental competitiveness of BE trucks
- > **Underlying assumptions**:
  - – CO_2 intensity of "grey" hydrogen: 9.00 kg / kg H_2
  - – CO_2 intensity of diesel: 2.64 kg/l
  - – CO_2 intensity of electricity: 0.51 / 0.30 kg/kWh (BE vehicle's WTW CO_2 emissions depend on development of energy mix in Europe)

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*) Green hydrogen

1) Assumed km/a of 80,000

2) BEVs' operational ability to service this segment questionable (different considerations for long-haul logistics vs. depot-based regional distribution use cases)

Source: FCH2 JU, Roland Berger; Gnann et al. 2017; NGVA Europe 2017

FC trucks can benefit from spillovers from cars and buses; specific challenges include infrastructure and heavy-duty requirements

Potential determinants of FCH truck competitiveness

Spillover effects from FCH sector development

- Technology spillover effects from the development and experience of passenger cars and buses (e.g. fuel cell stack production volumes) are expected to boost the competitiveness of FC trucks
- In particular, FC trucks could benefit from (sector-wide) performance improvements in the following areas:
  - Cold start ability
  - Lifetime
  - Production cost
  - Volume of fuel cell production
  - Standardization
  - Safety requirements
  - Consumer acceptance

Specific challenges for FC trucks

Influence of efficiency on TCO	The degree of powertrain efficiency determines much of a truck's TCO because of the high OPEX share (~75-80%[1] OPEX, fuel cost 30-45%); improvements of FCH efficiency thus highly beneficial, as expected efficiency gains for diesel trucks are relatively small
Influence of refuelling infrastructure	HRS are typically considered in the context of passenger cars or depot applications such as buses – long-haul trucks have more specific needs for refuelling determined e.g. by drivers' rest periods and routes (typical refuelling range of 300-350 km along major transport corridors)[2]
Reliability of FC trucks	Econ. value of truck loads puts great pressure on reliability; logistics companies are highly sensitive to downtime issues
Specific challenges for heavy-duty long-haul trucks	> Fuel storage: long-haul transport dependent on large onboard H_2 tanks, 700 bar storage likely necessary; size might compete with commercial truck load (generally solvable issue acc. to industry) > Truck tractors need engine output of up to 300 kW. Current FCH systems (e.g. from buses) need to be scaled up to this level

1) At current diesel prices 2) Assuming an average speed of 70 km/h, also in line with EU regulated rest periods for truck drivers

Source: Gnann et al. 2017; FCH2 JU, Roland Berger

Regulation will shape technology race for truck use cases; Regions and Cities can stage prototype demonstration projects

Key takeaways, opportunities and immediate implications for Regions & Cities

European, national and regional regulation will shape the future of different truck powertrain technologies; if zero-emission regulation for trucks is put in place (and low-emission alternatives like LNG, CNG, etc. are de-facto excluded from the technology mix), FC trucks could have distinct advantages in long-haul heavy-duty use cases (esp. vs. battery vehicles) due to superior ranges, shorter refuelling times and less adverse impact on payload cargo (same operations – in principle – as diesel trucks[1])

Short-term opportunities and immediate implications for Regions & Cities:

> Map local stakeholder landscape for truck use cases and potentially interested partners and discuss current level of interest in alternative powertrains for truck fleets

> Participate in prototype demonstration projects together with local partners to push technological readiness to the next level

> Closely monitor developments in the various demonstration projects across Europe in alignment with interested regional stakeholders

> Think or re-think hydrogen infrastructure roll-out strategy depending on potential needs of FC trucks in the region

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1) Operational equivalence to diesel dependent on H_2 tank size and onboard storage considerations

Source: FCH2 JU, Roland Berger

A.3 Urban buses

Fuel cell buses are a highly flexible zero emission option for public transport; they can in principle be operated like diesel buses

Value propositions of fuel cell hydrogen buses

High daily ranges

… of up to 400 km without refuelling – range extension possible

Full route flexibility

… not bound to any required infrastructure on the route

Strong performance

… comparable to diesel buses, e.g. acceleration or gradeability

Fast refuelling

… down to 7 min per bus possible – several refuelling cycles per day possible as well

High passenger comfort

… due to reduced noise levels and smooth driving experience

Close to full technological maturity

… with nearly 15 years and 10 million km of operational experience in Europe

Note: for a comparison of different alternative powertrain solutions, please refer to the FCH study "Urban buses: Alternative powertrains for Europe", 2012

Source: FCH2 JU, Roland Berger

We considered the deployment of 20 new buses from one depot, covering a typical distance of ~200 km per day and bus

Use case assumptions and exogenous factors in two scenarios – SIMPLIFIED

Use case

- Bus operator renews (part of) his fleet out of the same depot: deployment of ~20 new buses with routes of each ~200 km per day, i.e. annually ~65,000 km per bus
- Financing costs of bus operator: 5% p.a.
- Labour costs: based on 2 FTE per bus with average Western European wages of each EUR ~32,000 p.a.
- CAPEX for refuelling stations: one HRS at depot for FCH buses as well as substation, central transformer and cable charging infrastructure for BE buses; no additional investment considered for counterfactual diesel bus deployment
- Resulting hydrogen consumption (considering the assumptions on the next slide): ~15-20 kg per day (bus), ~350 kg per day (fleet)

Exogenous factors[1)]

- Cost of hydrogen for operator: 8.00 / 4.00 EUR/kg H_2
- Cost of diesel: 1.01 / 1.30 EUR/l
- Cost of electricity: 0.14 / 0.12 EUR/kWh
- CO_2 intensity of "grey" hydrogen: 9.00 kg / kg H_2
- CO_2 intensity of diesel: 2.64 kg/l
- CO_2 intensity of electricity: 0.51 / 0.30 kg/kWh
- NO_x intensity of diesel: 4.00 g/l (~1.5 g NO_x / km)

Strongly dependent on specific regional circumstances

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1) Two scenarios: "CURRENT" / "POTENTIAL"

Source: FCH2 JU, Roland Berger

Within our analysis we benchmark FC buses with electric as well as conventional diesel buses in a current and a future scenario

Application-related assumptions in two scenarios – SIMPLIFIED

CURRENT / POTENTIAL	**FCE Bus**	**BE Bus**[1]	**Diesel Bus**
Technical specifications	FCH-dominated powertrain	Overnight charging BE	Full diesel powertrain
	12 m; ~35-40 seats	12 m; ~35-40 seats	12 m; ~35-40 seats
	Holding period: 12 years	12 years	12 years
	Availability: 85% / 95%	90% / 95%	95% / 95%
CAPEX ('000 EUR)			
Purchase price	~620 / ~400[2]	~450 / ~350	~230 / ~250
Refuelling station	~2,400 / ~2,000	~1,000	-
Fuel			
Fuel type	Hydrogen (350 bar)	Electricity	Diesel
Consumption (per km)	0.086 / 0.065 kg	1.5 kWh	0.4 l
Maintenance costs (EUR)			
Bus per km	0.37 / 0.26	0.30 / 0.26	0.26 / 0.26
Refuelling station p.a.	~80,000	~30,000	~10,000
Replacements[2]	~60,000 / ~30,000	~90,000 / ~60,000	-

1) Guaranteed year-around ranges for BE buses will only become apparent through ongoing European procurements (2017-18), assumed range of 200 km/d in this use case is still TBC (potentially no feasible alternative in the "current" use case for ranges of 200 km)

2) Assuming production-at-scale scenarios for bus OEMs as per "Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe" (FCH JU, 2015)

3) One FC stack or battery pack replacement during lifetime

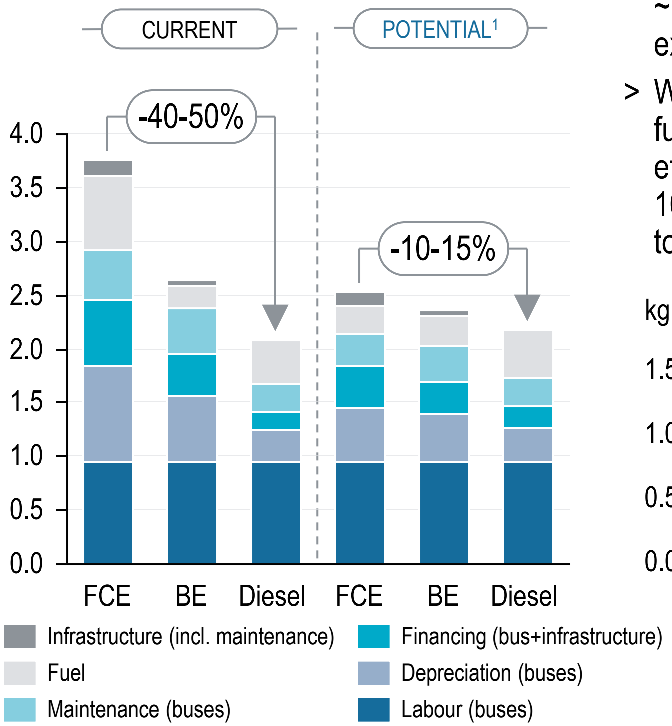
Source: FCH2 JU, Roland Berger

The cost premium of hydrogen buses might decrease significantly in the medium run, emissions can be drastically reduced

Business case and performance overview in two scenarios – INDICATIVE

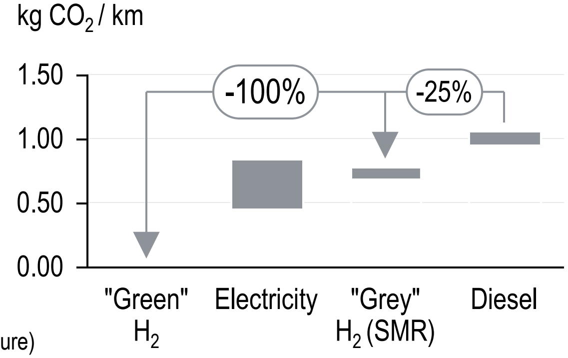
Economic

Total Cost of Ownership [EUR/km], annualised at 2017 prices



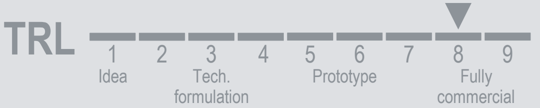
Environmental

- Zero tailpipe emissions of CO_2, pollutants (NO_X, SO_x) and fine dust particles, saving ~100 kg NO_X per bus a year (in this example)
- Well-to-wheel CO_2 emissions depend on fuel source (source of H_2, electricity mix, etc.) and vehicle efficiency, green H_2 or 100% green electricity would reduce well-to-wheel CO_2 emissions to zero



Technical/operational

- Fuel cell electric buses (full FC powertrain and FC range extender) are entering the commercial phase with large scale demonstration projects under way; besides, add. OEMs will launch vehicles in the short/medium run
- FC electric buses currently with availabilities of ~85% (longer down times), expected to reach ~95% in the medium run
- Range of FCH buses 250-450 km; (comparable to diesel buses), BE buses reaching 150-200 km max. guaranteed range
- Refuelling times of ~7-15 min per bus; comparable to diesel vs. BE bus several hours charging



1) The "POTENTIAL" scenario requires a number of FCE-related and other factors to fall in place in the medium/long run (please see previous slide)

Source: FCH2 JU, Roland Berger

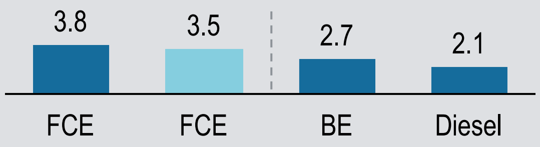
Impact of TCO drivers varies, opening up several leverage points for reduction of hydrogen TCO compared to diesel & electric TCO

Determinants of the TCO[1] – INDICATIVE

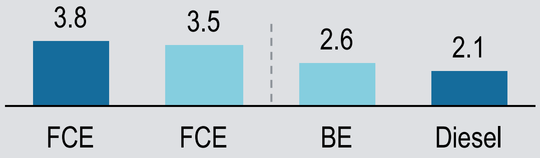
Key sensitivities considered (selection) …

… estimated impact on TCO [EUR/km]

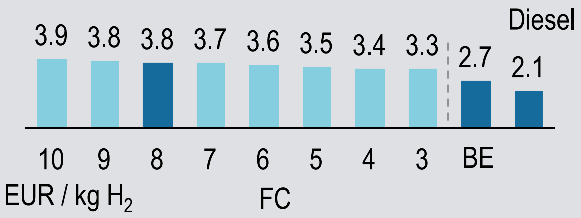
1 **Bus purchasing price:** reducing the bus purchasing price by 20% would lead to a reduction of the TCO of ~EUR 30 ct per km; total purchase price reductions to ca. EUR 400k per bus have been established by European studies ("POTENTIAL" scenario)



2 **Infrastructure costs:** setting attributable infrastructure investments for FCE buses (as well as electric buses) to zero, results in a potential TCO decrease of ~EUR 30 ct per km for FC buses



3 **Fuel costs:** reducing hydrogen costs to the operator from 10 EUR/kg H_2 to 3 EUR/kg, results in a potential reduction of TCO per km of ~60 ct or ~15-20%



■ TCO in EUR/km, base case □ TCO in EUR/km, adjusted variables

[1] Unless otherwise stated, all statements shall be considered *ceteris paribus*, i.e. "all-other-things-equal"

Source: FCH2JU, Roland Berger

Please note the following:

> *Today's analysis showed one hypothetical example of a multi-dimensional performance comparison between FCE, BE and diesel buses. Real-life projects will differ based on regional circumstances and have to consider a range of additional factors (e.g. specific routes and schedules, individual bus-related requirements, national labour laws, additional cost items such as e.g. insurance and depot-related costs) that this high-level analysis omitted for simplification purposes*

> *Similarly, the scenarios shown above should be interpreted as potential combinations of key variables that affect the comparative technology performance*

> *Please note that a number of (industry-based) studies on FCE buses have been published under the auspices of the FCH2 JU over the past years. Please consult them for further reading:*

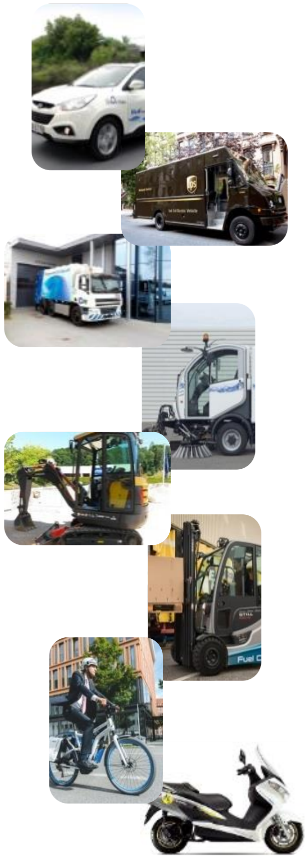
- *"New Bus ReFuelling for European Hydrogen Bus Depots", 2017*
- *"Clean Hydrogen in European Cities (CHIC) – Final Report", 2017*
- *"Strategies for joint procurement of fuel cell buses", 2017*
- *"Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe", 2015*
- *"Urban buses: alternative powertrains for Europe", 2012*

Source: FCH2 JU, Roland Berger

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

The diverse Working Group 2 covers the most mature application (forklifts) as well as early stage prototype endeavours

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

Holthausen Groep, Air Liquide, Ceres Power, atawey, Daimler, Proton Motor, Calvera, Fronius, Ballard, SEMA consulting, HyET Hydrogen, ITM Power, The Linde Group, Logan Energy, H2B2, BMW Group, Mercedes-Benz, Hydrogenics, ariema, Toyota, uniper, Plug Power Europe

Source: FCH2 JU, Roland Berger

Each analysis consist of 3 key elements (use case, technologies, performance) – Regional differences will be tackled in Phase 2

Prel. business case components and flow of analysis – SCHEMATIC

Exogenous assumptions, e.g. energy/fuel cost, carbon intensities

FCH application

- > Technical features (e.g. output, efficiency, lifetime, fuelling requirements) and general readiness
- > Est. CAPEX / system cost
- > Est. OPEX (e.g. maintenance)

… plus benchmarking against competing technologies

1 "generic" use case

...consisting of typical deployment requirements of European regions and cities

Basic performance

- Technical / operational
- Economic
- Environmental

Source: FCH2 JU, Roland Berger

B.1 Cars

Each customer segment has a distinctive user profile resulting in different priorities with respect to their purchase decision

FCEV: customer segmentation, share of new vehicles & respective purchasing criteria

	1 **Private individual customers**	2 **Company car customers**	3 **Commercial fleet operators**
			
Characteristics	> Exclusively private use of the vehicle > Low mileage (typically less than ~10,000 km p.a.) > Holding period ca. 7 years	> Private and business-related use of the vehicle > Medium mileage (~20,000 km p.a.) > Holding period ca. 3 years	> Exclusively commercial use of the vehicle (company fleet) > High mileage (up to ~40,000 km p.a.) > Holding period ca. 3-4 years
Share of new vehicles	~40%	~30%	~30%
Purchasing criteria			
> Vehicle cost	● Decisively relevant (purchasing price)	● Decisively relevant (purchasing price)	● Decisively relevant (TCO)
> Technology performance	◑ Partly relevant	◔ Not very relevant	◑ Partly relevant
> External influences	◑ Partly relevant	◑ Partly relevant	◔ Not very relevant
> Infrastructure / charging patterns	◑ Partly relevant	◕ Very relevant	◕ Very relevant

Source: NPE, FCH2 JU, Roland Berger

As an example, we consider a public procurement of FCEV at the municipal level, with different cost and performance parameters

Key assumptions – INDICATIVE EXAMPLE

Application-related assumptions

current/potential	**FCEV**	**BEV**	**Diesel**
Technical specifications	Mid-range car	Mid-range car	Mid-range car
> Holding period:	4 years	4 years	4 years
CAPEX ('000 EUR)			
> Purchase price	70 / 35[1]	35 / 30	31 / 31
> Ref. station	-	-	-
> Residual value	50%	50%	40%
Fuel			
> Fuel	Hydrogen (750 bar)	Electricity	Diesel
> Consumption (per km)	0.008 kg	0.13 kWh	0.043 l
Maintenance costs (EUR)			
> Car per km	0.023	0.018	0.023

Use case and exogenous factors

Strongly dependent on reg. circumstances

- A municipal authority has a total vehicle fleet of ~300 medium-sized vehicles, potentially resembling a city with ~500,000 inhabitants. Ca. half of these vehicles are operated by police, emergency services and the fire brigade, each with specific requirements. The other half, e.g. vehicles for social services, are considered in this context.
- Hence, the operator deploys ~30 new vehicles with each vehicle travelling ~100 km a day, five days a week (~220 days of a year) on average, covering a total of ~660,000 km p.a.
- The vehicles hydrogen consumption: ~0.8 kg/d (1 car), ~24 kg/d (fleet)
- Financing costs of operator: 5% p.a.
- Context for refuelling infrastructure: this base case assumes existing availability of public refuelling infrastructure for FCEV, BEV and diesel vehicles

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- Source of hydrogen: Steam-Methane Reforming (SMR), truck-in
- Cost of hydrogen: 9 / 5 EUR/kg H_2
- Cost of diesel : 1.2 / 1.4 EUR/l
- Cost of electricity: 0.21 / 0.30 EUR/kWh
- CO_2 emissions from grey hydrogen: 9 / 9 kg / kg H_2
- CO_2 emissions from diesel: 2.64 / 2.4 kg/l
- CO_2 emissions from electricity: 0.51 / 0.3 kg/kWh

Strongly dependent on reg. circumstances

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[1] Assuming production-at-scale scenarios for vehicle OEMs, current price of diesel cars as initial target price for FCH cars (preliminary – to be validated)

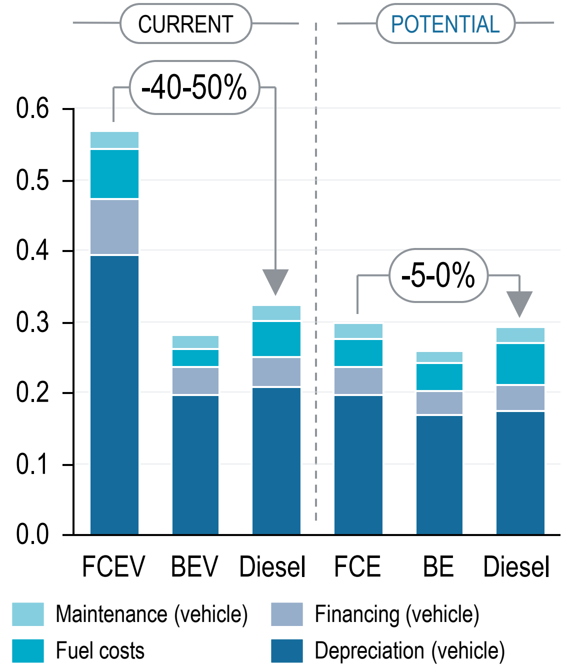
Source: FCH2 JU, NOW, Roland Berger

FCH cars might almost reach cost parity with electric and diesel vehicles in the medium run, while reducing CO_2 and NO_x emissions

Business case and performance overview – INDICATIVE EXAMPLE

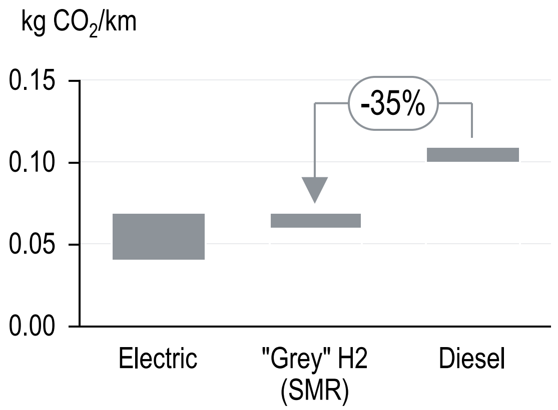
Economic

Estimated annualised Total Cost of Ownership (TCO) [ct/km], 2017 prices



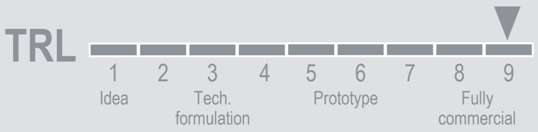
Environmental

- > FCEV have zero tailpipe emissions of CO_2, pollutants such as NO_X and fine dust particles, e.g. saving ~115 kg NO_X/year compared to diesel fuelled vehicles
- > Well-to-wheel CO_2 emissions depend on fuel source, power mix, use case and efficiency (i.e. fuel consumption):



Technical/operational

- > FCEV technology is commercially ready with leading OEMs offering selected models in serial production; widespread market introduction depending on expansion of hydrogen refuelling infrastructure and economies of scale / learning-curve effects to lower the premium on the product cost
- > FCEV have a range of approx. 350 – 700 and can reach top speeds of up to 160 km/h
- > Refuelling process & times of FCEV are, with a duration of ~3-4 minutes, comparable to conventional combustion engine vehicles



Source: FCH2 JU, Roland Berger

The impact of TCO-drivers varies, creating several levers for further reduction of hydrogen TCO compared to electric and diesel TCO

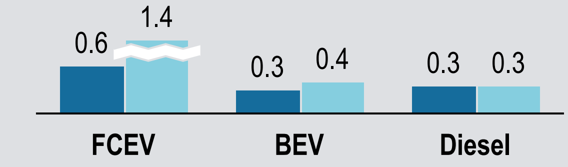
Key determinants of the business case – INDICATIVE EXAMPLE

Important sensitivities considered ...

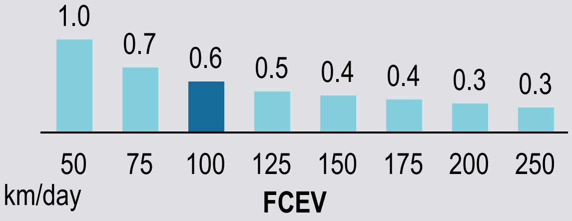
... estimated impact on TCO

[EUR/km]

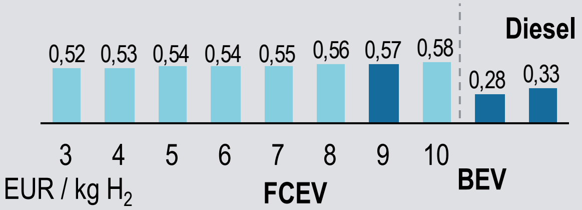
1 **Infrastructure:** if additional infrastructure investments for fleet operator are included (i.e. in a pure captive fleet case), such as refuelling stations for FCEV (and BEV), this ca. doubles TCO per km



2 **Mileage per day:** varying the mileage of vehicles per day from 50 to 250 km, might result in a potential TCO decrease of ~EUR 0.70 ct **– strong use-case dependent differences**



3 **Fuel prices:** a price variation from EUR 10 to EUR 3 per kg H_2, potentially reduces overall TCO costs by ~10 ct **– prices for H_2 can vary significantly across Europe**



■ TCO, base case ■ TCO, adjusted variables

1) Unless otherwise stated, all statements shall be considered as 2017-based and ceteris paribus, i.e. "all-other-things-equal"

Source: FCH2 JU, Roland Berger

In order to successfully deploy an FCEV fleet, regions & cities can take specific steps

Key considerations for Regions and Cities deploying FCEV

Use case

Look for use cases with critical concern for range (>200 or even 300 km per day) as well as refuelling time

Customers

Consider especially approaching and incentivizing key fleet customers, e.g. taxis, ride- and carsharing operators, small-vehicle delivery services, social services in order to better distribute CAPEX for e.g. infrastructure

Emissions

Look for availability of green H_2 in order to seize full well-to-wheel zero emission potential of FCEV

Source: FCH2 JU, Roland Berger

B.2 Delivery Vans

FC-hybrid/electric delivery vans fulfil many requirements operators are interested in

Advantages of FC-hybrid/electric delivery vans

- FC electric or hybrid delivery vans are 0-emission vehicles, complying with inner-city regulations on 0-emission zones. FCH delivery vans could also potentially benefit from special night-delivery permits for low-noise vehicles
- Already today, technologies for FC-hybrid/electric delivery vans demonstrate ranges sufficiently long to cover typical driving perimeters around distribution centres – and could particularly do so in longer-range use cases (suburban or rural delivery), as full FCH powertrain or range extender solutions
- Refuelling can be conducted at public H_2 refuelling stations and/or company-owned depot stations, short refuelling times minimize interruptions in the daily operating schedule
- Maintenance and fuel costs of FC-hybrid/electric delivery vans are outperforming costs of conventional diesel powertrains

Source: FCH2 JU, Roland Berger

Vehicles for all types of operators are available since the delivery van market covers highly heterogeneous use cases

Types of delivery vans by category and available technologies

INDICATIVE

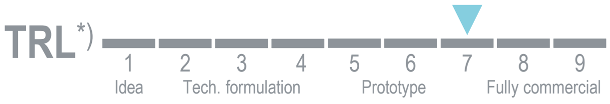
				
Load bed	ca. 1,000 l	ca. 5,000 l	ca. 10,000 l	ca. 35,000 l
Exemp. Model	e.g. Renault Kangoo	e.g. VW Transporter	e.g. Mercedes Sprinter	e.g. Iveco Daily
Description – Use case (examples)	Just-in-time delivery of e.g. perishable goods or courier deliveries to close-by inner-city surroundings	Transportation and selected stock keeping of replacement parts and tools for craftsmen	Inner-city and regional delivery of parcels from distribution centres to the final customer	Regional delivery of larger parcels and bulky goods (e.g. furniture elements)
Range [per day]	30 – 150 km	30 – 150 km	30 – 350 km	30 – 250 km
Available technologies	FCEV, FC hybrid, BEV, CNG/LNG, Diesel	FCEV, FC hybrid, BEV, CNG/LNG, Diesel	FCEV, FC hybrid, BEV, CNG/LNG, Diesel	FCEV, FC hybrid, BEV, CNG/LNG, Diesel
Engine output	45 – 60 kW	50 – 150 kW	60 – 110 kW	70 – 150 kW
Consumption	Highly dependent on the individual use case, for example type of good transported, number of stops per day, rural or urban area of operation, etc.			

Source: Symbiofcell, Volkswagen, i.wheelsage, Truck1, National Renewable Energy Laboratory, FCH2 JU, Roland Berger

Already today, a variety of FC-hybrid/electric vehicle types have been prototyped successfully or are even already deployed

Status of fuel cell hybrid/electric delivery vans

Overall technological readiness: FCEV delivery vans are still in proof-of-concept phase, use cases are predominantly centred 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 170 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
HyWay[1]	🇫🇷	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 partagé[1]	🇫🇷	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

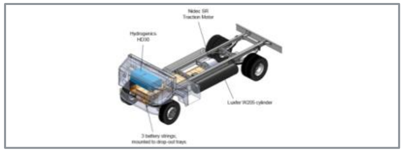
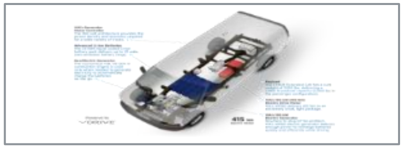
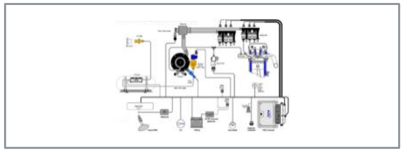
*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Source: FCH2 JU, Roland Berger

Due to their superior range and refuelling times as well as their low emissions, FC-hybrid/electric vans are an attractive alternative

Average powertrain parameters for delivery vans < 3.5 t

INDICATIVE

		1 FCH Delivery Truck	2 BE Delivery Truck	3 Diesel Delivery Truck
				
CAPEX [EUR]	**Actual 2015**	149,400-165,200	68,900-76,200	28,500-31,500
	Estimate 2030	51,300-56,800	53,300-58,900	35,600-39,500
Consumption [kWh/km]	**Actual 2015**	0.58-0.64	0.33-0.37	0.7-0.78
	Estimate 2030	0.49-0.55	0.29-0.32	0.58-0.64
Maintenance [EUR/km]	**Actual 2015**	0.23-0.25	0.09-0.1	0.09-0.1
	Estimate 2030	0.05-0.06	0.05-0.04	0.09-0.1
Refuelling time[1]		Low ◔	High ●	Low ◔
Range[1]		Medium-high range ◑	Low-medium range ◔	High range ●
Key challenges		Commercial availability (only prototypes in the market), size of hydrogen tanks for sufficient daily range without return to depot	Cost, size and weight of batteries; range restricts delivery service in less densely populated operational areas	CO_2 and NO_x emissions and related regulation as well as noise pollution, particularly in the inner city operational areas
TRL level		Level 6 - 7	Level 8 - 9	Level 9

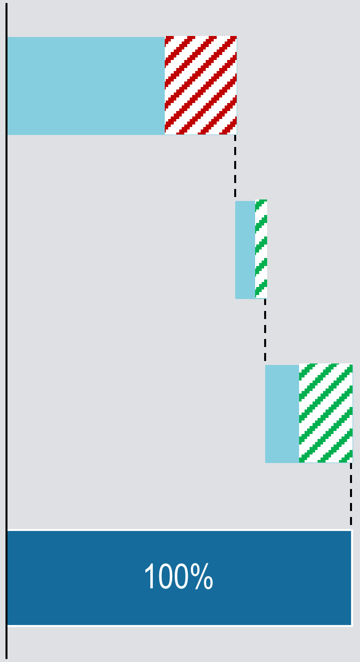
[1] Expected, still being tested and under constant development

Source: Gnann et al. 2017, Bentley Truck Service, VIA Motors, Center for Transportation and the Environment (CTE), FCH2 JU, Roland Berger

However, FC delivery vans need a competitive advantage on OPEX in order to benchmark well against the powertrain competition

Schematic outline of TCO for FC delivery vans and its drivers – SIMPLIFIED, INDICATIVE

Total Cost of Ownership (TCO), e.g. in EUR per km



	Diesel	Battery electric	Fuel cell
Capital cost	> Lower price per kW power > Maturity level reached, low development costs > Conventional fossil fuel refuelling stations can be used	> Higher costs per kW > High development costs starting to decrease due to increasing production > High investments in company owned recharging stations or reliance on public stations	> Highest costs per kW > Highest development and permitting costs > High investments in company owned refuelling stations or reliance on public stations
Op's & maint. cost	> High maintenance costs > Less expensive spare parts	> Frequent maintenance routine for batteries necessary > Moderately priced spare parts	> Less frequent maintenance routine, lower maintenance costs > More expensive spare parts
Fuel cost	> Highest fuel costs per km > Higher maintenance cost	> Lowest fuel costs per km > Low carbon footprint	> Low fuel costs per km, potentially further decreasing over time > Low carbon footprint

Take-away

Currently, high capital costs make fuel cells the more expensive alternative. However, further improvements in production and fuel price reductions can lead to a superior cost position in comparison to combustion engines and battery electric vehicles in the future. Focus on longer-range use cases and possibly range-extender solutions might be warranted

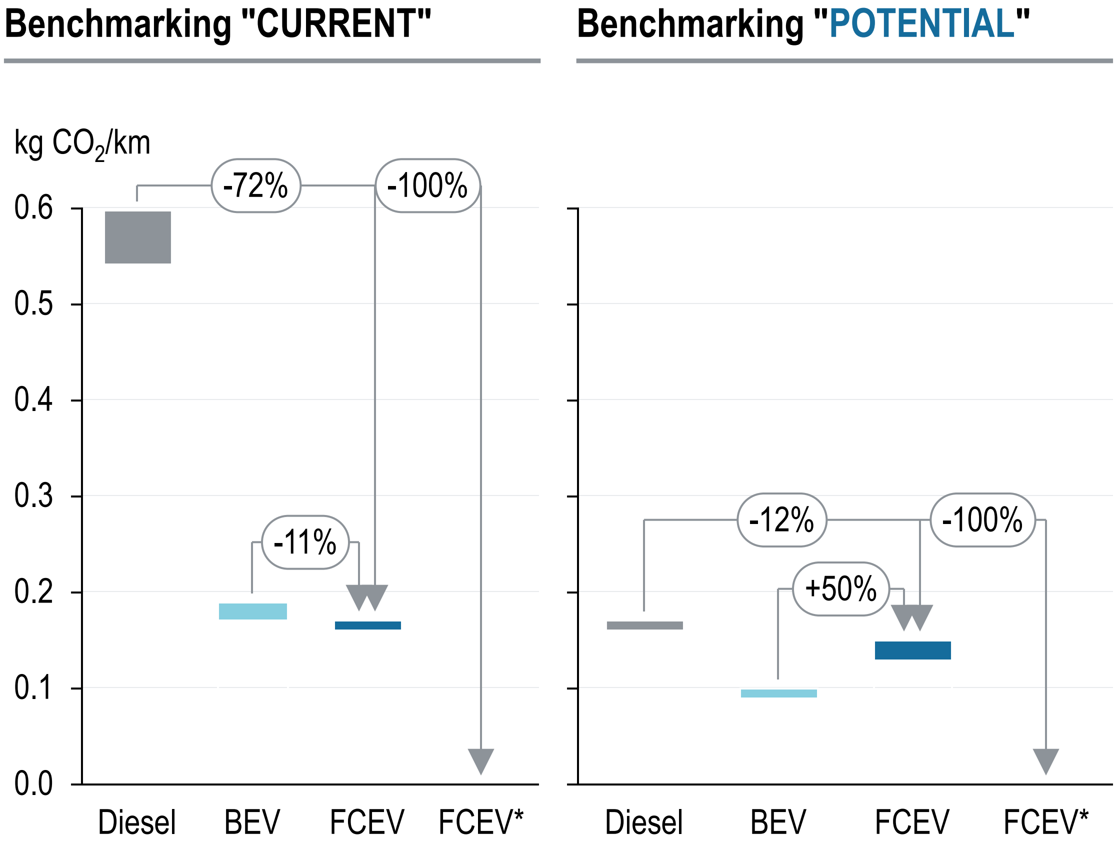
▨ Additional **cost** range for alternative powertrains ▨ Range for additional **savings** through alternative powertrains

Source: FCH2 JU, Roland Berger, Shell

Currently, fuel cell delivery vans are the cleanest option amongst the competing technologies but BE delivery vans are set to catch up

WTW emissions benchmarking

INDICATIVE



*) Green hydrogen

- **Key drivers:**
  - Availability of green hydrogen is decisive in outperforming the benchmark technologies
  - Development of the energy mix highly determines the environmental competitiveness of FCE delivery vans vs. BE vans
- **Underlying assumptions:**
  - CO_2 intensity of "grey" hydrogen: 9.00 kg / kg H_2
  - CO_2 intensity of diesel: 2.64 kg/l
  - CO_2 intensity of electricity: 0.51 / 0.30 kg/kWh (the BEV's CO_2 advantages depend on the development of the energy mix in Europe and the assumption that range issues will be overcome)

Source: Fraunhofer Institute, FCH2 JU, FCH2 JU, Roland Berger

BEVs for now take most of the early conversion markets for urban last-mile delivery; FCs see potential in longer-range use cases

Immediate implications for Regions & Cities in the short term

Until now, battery electric delivery vans already capture parts of the 0-emission conversion opportunities for urban/suburban last-mile delivery vans (~100 km/d range, e.g. "Streetscooter" in Germany), benefitting from cost and performance improvements of BEVs overall; FCH vehicles might better focus on **longer-range use cases** (e.g. rural delivery services) **or special purpose vehicles with extra energy needs** such as delivery vans with permanent cooling either as full powertrain or as range extender solutions. In such uses cases, larger batteries might reduce the payload of the vehicle. Non-powertrain related disruptions are another key determinant of future vehicle market volumes

Short-term opportunities and immediate implications for Regions & Cities:

- Map local stakeholders and discuss potential FC delivery van applications – support the development of interest groups and demonstration projects
- Incorporate battery and FC range extenders into potential portfolio of alternatives to increase the applicability of fuel cells
- Closely monitor developments in the various demonstration projects across Europe in alignment with interested regional stakeholders
- Think or Re-Think the hydrogen infrastructure roll-out strategy depending on potential needs of FC-electric/hybrid delivery vans in the region

Source: FCH2 JU, Roland Berger

B.3 Garbage trucks

Use case and applications determine capital, fuel, O&M and infrastructure cost that in turn make up the operator's TCO

Key elements of FCH transport applications' TCO – SCHEMATIC, SIMPLIFIED

Operator's perspective ...

The task / scenario at hand: use case, deployment context, target operating model, e.g.

- Route definition and length, required stops/stations
- Target capacity
- Target shift schedule for operations
- Target availability
- Topographic and other ext. conditions
- Fleet size, depot structure
- Energy cost
- Carbon intensities
- ...

FCH truck / system specifications and performance

- Size, volume, weight, other physical configurations
- Maximum / average speed
- Powertrain design, i.e. fuel cell + battery / other hybridisation + engine
- Fuel cell technology
- Efficiency / fuel consumption
- Hydrogen storage system
- Lifetime
- Availability
- ...

Hydrogen infrastructure specifications and performance – sharing ratios

1. Capital cost

- Investment / depreciation,
- Financing cost

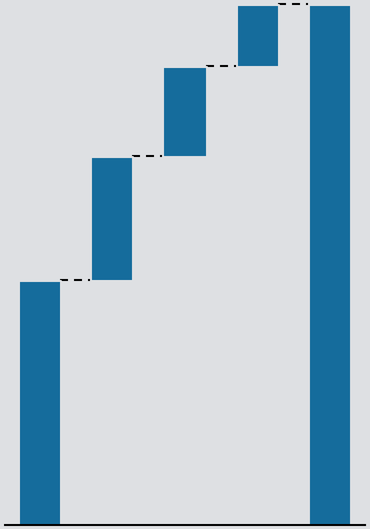
2. Fuel cost – H_2 consumption, H_2 price (dep. on production, distribution, volumes, input prices, etc.)

3. Other O&M cost, e.g. for truck maintenance, personnel, utilities, fees/levies, taxes[1]

4. Infrastructure cost

- Investment / depreciation
- O&M cost

Total Cost of Ownership (TCO) in EUR p.a. or EUR/km



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1) Largely excluded for preliminary business case analysis, more detailed consideration in Project Phase 2

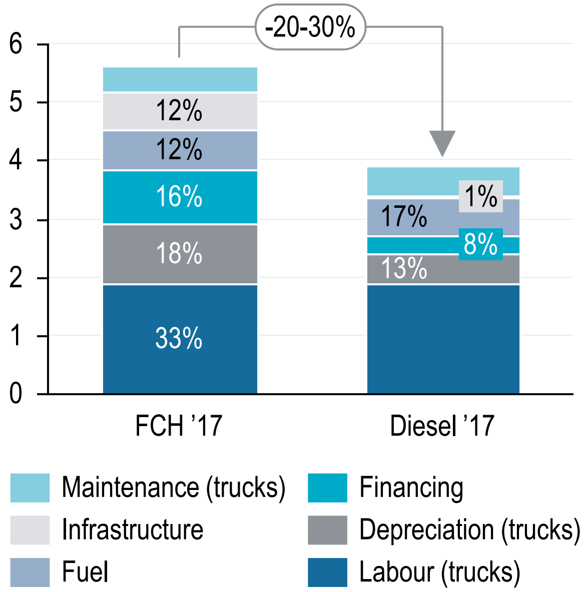
Source: FCH2 JU, Roland Berger

There is a cost premium for FCH trucks for each km travelled and a significant CO_2 emission reduction potential of ~25-35%

Business case and performance overview – INDICATIVE EXAMPLE

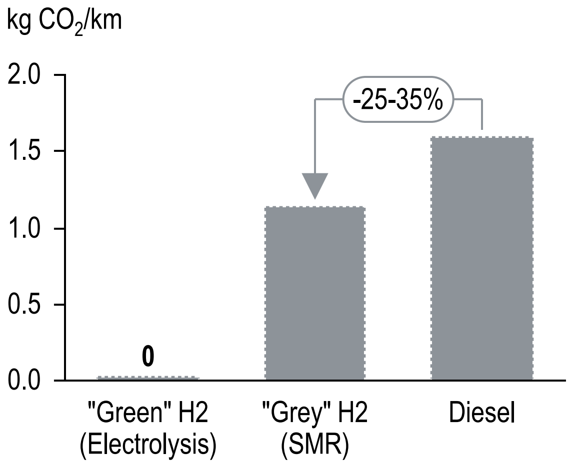
Economic

Estimated annualised Total Cost of Ownership (TCO) [EUR/km], 2017 prices



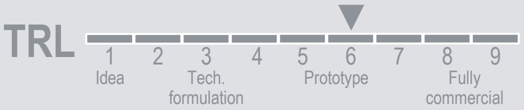
Environmental

- > Zero tailpipe emissions of CO_2, pollutants such as fine dust particles and NO_X, saving ~80-100 kg NO_X/year
- > Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption)



Technical/operational

- > So far, only electric trucks with hydrogen fuel cell range extender (e.g. in Eindhoven) or conventional diesel combustion powertrain with hydrogen fuel cell power-box for loader and compactor (e.g. in Berlin) as prototype demonstration; only conceptual studies for entire fuel cell garbage truck publicly disclosed (e.g. in Honolulu, HI, U.S.)
- > FC powered garbage trucks currently have an availability of ~85% due to higher down times, with reliability expected to reach 95% eventually
- > Range[2] of FC electric garbage trucks likely up to ~360 km, similar to diesel



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1) Analysis is based on a hydrogen vehicle with both, hydrogen propulsion as well as hydrogen "power-box", consisting of the loader and compactor

2) Specification based on the DAF CF FA freight truck with hydrogen as a range extender, deployed within the project *Hydrogen Region for Flanders and the southern Netherlands*

Source: Life `N Grab H4, U.S. DoE, FCH2 JU, Roland Berger

The impact of drivers on vehicle economics varies, creating several levers for further reduction of hydrogen TCO compared to diesel

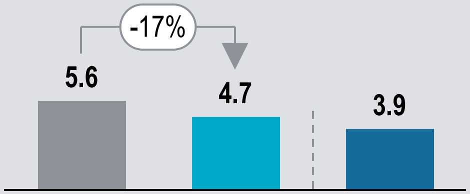
Key determinants of the business case[1] – INDICATIVE EXAMPLE

Sensitivities considered …

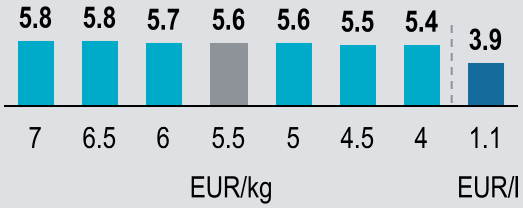
… est. impact on TCO [EUR/km]

1 **Garbage truck purchasing price:** reducing the hydrogen garbage truck purchasing price by 20% might lead to EUR 30 ct reduction of TCO per km

2 **Infrastructure costs:** excluding infrastructure costs in the hydrogen case, i.e. levelling of infrastructure expenditure in both cases to EUR 0, could result in a decrease of the TCO per km of EUR 90 ct – **infrastructure costs strongly dependent on fleet size and depot structure**



3 **Fuel costs:** reducing the fuel costs for hydrogen supply from EUR 7 per kg H_2 to 4, results in a potential reduction of total costs per km of EUR ~40 ct – **strong regional differences for H_2 prices**



■ FCH truck TCO, base case ■ FCH truck TCO, adjusted variables ■ Diesel truck TCO, base case

[1] Unless otherwise stated, all statements shall be considered *ceteris paribus*, i.e. "all-other-things-equal"

Source: Life `N Grab H4, U.S. DoE, FCH2 JU, Roland Berger

Similarities regarding lifetime, costs of labour and maintenance for FCH trucks likely, differences in CAPEX investment for HRS

Key assumptions – INDICATIVE EXAMPLE

Application-related assumptions[1]

	FCH side-loader	Diesel side-loader
Technical specifications	Full FCH vehicle Weight: ~24 t Lifetime: 12 years Availability: 85%	Full diesel vehicle Weight: ~20 t Lifetime: 12 years Availability: 95%
CAPEX		
> Purchase price	~ EUR 400-450k	~ EUR 200-220k
> Initial HRS	~ EUR 2.4 m	-
Fuel		
> Fuel type	Hydrogen (350 bar)	Diesel
> Consumption (/km)	~0.120-130 kg	0.6 litre
> Consumption (/day)	~20-25 kg	110 litre
Maintenance costs		
> Trucks	0.40-0.50 EUR/km	0.5 EUR/km
> Ref. station p.a.	EUR 70-75k	EUR 10,350
Labour costs p.a.	EUR 64,000	EUR 64,000

Use case and exogenous factors

Strongly dependent on reg. circumstances

- Municipal waste management company with need to renew (part of) its 150 garbage truck fleet. First tranche of ~12 vehicles to be purchased. Overall coverage of ~400,000 km per year, with a daily distance covered by a single truck of ~180 km within a 5-day week at an average speed of ~15 km/h
- Financing costs of waste management company : 5% p.a.
- Labour costs: based on 2 FTE per truck with averaged Western European wages of EUR 32,000 per year
- CAPEX for refuelling stations: one HRS considered at depot for FCH buses; for counterfactual diesel truck deployment not add. investment considered due to wide-spread availability of diesel refuelling infrastructure today

- Source of hydrogen: Steam-Methane Reforming (SMR), truck-in
- Cost of hydrogen for operator: ~5.5 EUR/kg H_2
- Cost of diesel : 1.1 EUR/l
- CO_2 emissions from grey hydrogen: 9 kg/kg H_2
- CO_2 emissions from green hydrogen: 0 kg/kg H_2
- CO_2 emissions from diesel: 2.64 kg/l
- No_x emissions from diesel: 4 g/l

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[1] Tech. spec. based on fully hydrogen powered garbage truck deployment as simulated in the *Fuel Cell –Electric Refuse Truck for Waste Transportation* study (DoE, 2015)

Source: FCH2 JU, Life `N Grab H4, U.S. DoE, Roland Berger

B.4 Sweepers

FCH sweepers are a highly flexible zero emission option and have a comparatively high utilization rate

Value propositions of fuel cell hydrogen sweepers

Long ranges

… of 12-16 hours deployment without refuelling – range extension possible

Strong performance

… comparable to diesel sweepers, e.g. acceleration or gradeability

High operational variability

… due to GHG and noise emission reduction, add. appl. areas like warehouses and railway stations feasible

High utilization

… compared to diesel powered alternatives due to strong reduction of noise and resulting overnight deployment options

Fast refuelling

… down to 5-7 minutes per vehicle possible – several refuelling cycles per day possible as well

On the way to full technological maturity

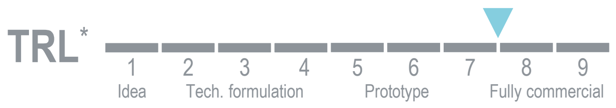
… with several FCH sweeper demonstration projects underway

Source: FCH2 JU, Roland Berger

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

Fuel cell sweepers – updated abstract from Technology Introduction

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 deployment for California Department of Transportation (Caltrans)	🇺🇸	2017	Manufacturing of fuel cell powered street sweeper by Global Environmental Products in California, for 24/7 deployment after successful five year testing of diesel hybrid solutions	n.a.
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.

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: FCH2 JU, Roland Berger

Besides emission reduction, FCH sweepers offer higher utilization rates due to noise reduction and large operating ranges

Benchmarking with comparable street sweepers

INDICATIVE

	FCH Sweeper A	**BE Sweeper** B	**Diesel Sweeper** C
Description	Fuel cell hydrogen powertrain for propulsion and brush rotating system	Battery electric powertrain for propulsion and brush rotating system	Conventional, diesel-based powertrain for propulsion and brush rotating system
Specifications			
Costs[1]:	400,000 – 450,000	400,000	280,000 – 300,000
Powertrain:	30 kW FC with 108 kW (700 bar)	48 V, 1,000 Ah	50 – 80 kW
Range:	12 – 16 hours	4 – 9 hours	12 – 16 hours
Weight (unloaded):	5 – 6 t	4 – 5 t	5 – 6 t
Max. speed:	30 – 40 km/h	25 – 35 km/h	30 – 50 km/h
Key benefits and challenges	⊕ Zero local GHG and noise emissions ⊕ Fast recharging ⊕ Large operating ranges (e.g. at night) ⊖ CAPEX premium due to tech. maturity ⊖ Usually, add. charging infrastructure required	⊕ Zero local GHG and noise emissions ⊕ Usually no additional infrastructure required ⊖ Long recharging times ⊖ Limited operating ranges	⊕ Reliable technology ⊕ Fast refuelling ⊕ No additional infrastructure requirements ⊖ Local emission of CO_2 and NO_X among others ⊖ Noise pollution

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1) CAPEX expenditure for the entire vehicle, including the base chassis as well as the conversion/integration

Source: FCH2 JU, Roland Berger

FC Sweepers are not fully commercialized yet, but large ranges and lower noise emissions emphasize their future potential

Business case and performance overview – INDICATIVE

Economic

> **Higher system efficiency**, lower maintenance and operating costs are counterbalancing relatively higher capital costs of FC sweepers vs. conventional powertrains

> **Short refuelling times** and long ranges increase availability rates in comparison to battery-electric sweepers and hence potentially improve the profitability

> **Key business case drivers**:
  – CAPEX resulting from system integration
  – Additional infrastructure costs, esp. refuelling station CAPEX (incl. utilisation) and OPEX
  – Potential 24/7 operations significantly improve utilization rate (depending also on regulation and costs among others)

Environmental

> **Zero tailpipe (i.e. tank-to-wheel) emissions** of CO_2, pollutants such as NO_X and fine dust particles for FCH sweepers – key benefits for outside environment, including other workers, passer-by and residents

> **Lower noise emissions as key benefit for operations**, esp. during night time deployment in urban environments

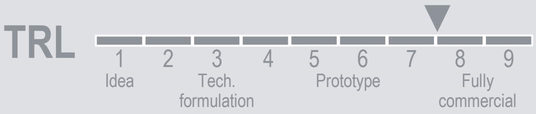
> Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-wheel emissions for FCH sweepers with "green hydrogen"**

Technical/operational

> **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 indicating close to technological maturity

> **Demonstration projects** in operational environment have been **completed** or are currently **ongoing**

> **Similar operational characteristics** to be expected as diesel-combustion sweepers (e.g. refuelling times, flexibility, ranges)



Source: FCH2 JU, Roland Berger

B.5 Construction mobile equipment

Use case of FC constr. mobile equ. and respective infrastructure req. are highly dependant and adjustable according specific needs

Use case characteristics

Description

- > Fuel cell construction mobile equipment such as tractors, excavators or crawlers either use fuel cells as a range extender for batteries (hybrid concept) or to fuel the complete machine including drivetrain and auxiliary systems
- > Vehicles are refuelled directly at the construction site, either by tank trucks or small independent refuelling stations

Technical characteristics

- > Changing the type of powertrain mostly requires to redesign the vehicle in order to ensure sufficient vehicle counterweight
- > Necessary engine output is strongly dependent on the specific type of vehicle (e.g. 75 kW for a FC tractor)
- > Significant noise reductions of ca. 10 dB out- and 20 dB inside compared to diesel counterfactuals can be realized

Competing technologies

- > Diesel, Battery-Electric, Diesel-battery hybrid

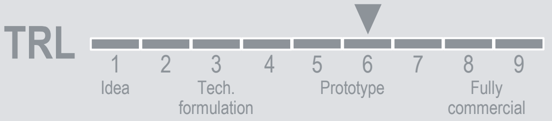
Source: Industry publications, Symbiofcell, Volvo, New Holland, FCH2 JU, Roland Berger

FC construction mobile equipment is still in a prototyping stage and not fully commercialized yet, with several domo projects ongoing

Business case and performance overview – INDICATIVE

Technical/operational

- > 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
- > Volvo, Hyundai and New Holland can be regarded as OEM pioneers while fuel cells are mostly supplied by Symbio FCell or Hyundai



Economic

- > **Higher system efficiency,** lower maintenance and operating costs are counterbalancing high CAPEX costs
- > **Noise reductions** possibly enable construction companies to increase their operating hours and hence reduce overall construction times
- > Additional infrastructure costs to set up a refuelling infrastructure are limited since construction mobile equipment is fuelled by tank trucks or independent on-side refuelling stations – **switch from diesel to hydrogen relatively easy**
- > **Key business case drivers**:
  - – Cost of hydrogen vs. cost of diesel
  - – System CAPEX

Environmental

- > **Zero tailpipe (i.e. tank-to-wheel) emissions** of CO_2, pollutants such as NO_X and fine dust particles as well as significant noise reduction for FCH construction mobile equipment – key benefit for workers as well as outside environment
- > Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-wheel emissions for FCH construction mobile equipment with "green hydrogen"**

Source: FCH2 JU, Roland Berger

Since decarbonisation is high on the agenda of authorities, FC systems could to become part of the technology pool in the long run

Key considerations concerning fuel cell mobile construction equipment

To be validated by demo projects

- **Authorities place increasing importance on decarbonisation and emissions reduction** and hence stimulate the development of zero-emission engines for construction mobile equipment – additionally, **supranational regulations** from EU-level will require CO_2 monitoring and 'cap and trade' policies might be introduced in a second step
  - **FC mobile construction equipment will not only help to achieve these targets, but also drastically reduce noise emissions,** thereby improving the quality of life of local residents affected by constructions, especially during the **night**
- **Necessary size /power ranges, capital cost and fuel supply** are among the major **hurdles** faced by fuel cell powered mobile construction equipment
- **Short refuelling times** and independent on-site refuelling stations facilitate the process of switching from diesel to hydrogen
- Further **demonstration projects** will be necessary to **increase technological readiness and foster commercial availability**

Source: FCH2 JU, Roland Berger

B.6 Material handling equipment, esp. forklift trucks

We consider the deployment of a sizeable fleet of forklifts for a large warehouse, comparing FCH forklifts to battery-powered forklifts

Use case characteristics and key exogenous assumptions

Use case characteristics

CURRENT / POTENTIAL[1]

- The assumed warehouse operator services 30,000 – 40,000 m^2 warehouse space, deploying ~100 new forklifts (for example ~2/3 pallet forklift trucks, ~1/3 larger forklift trucks, e.g. reach trucks). The forklifts operate approx. 330 days a year in a two-shift system with 7 working hours per shift, resulting in ca. 4,620 operating hours p.a. per forklift.
- Operators typically face technology decision (mainly) between battery-powered and FC-powered forklifts (mainly) for indoor operations
- Refuelling: one hydrogen refuelling station with ~30 m^2 at central depot for FCH forklifts; ~120 m^2 depot with charging stations and manned battery-exchange facilities required for counterfactual electric forklift truck deployment

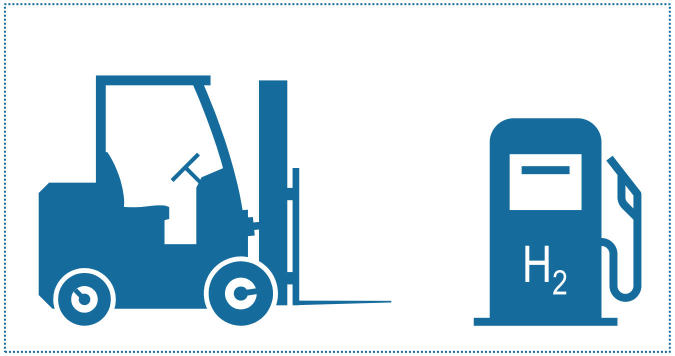
Strongly dependent on reg. circumstances

Key other assumptions

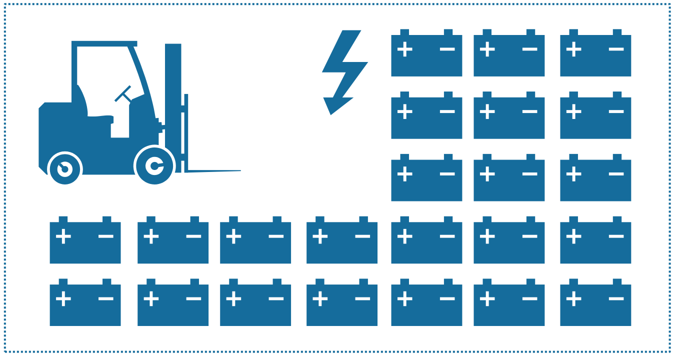
CURRENT / POTENTIAL[1]

- Cost of hydrogen: for example 8.00 / *4.00* EUR/kg H_2
- Cost of electricity: for example 0.14 / *0.18* EUR/kWh
- No policy support (e.g. subsidies) to be considered initially, but possibly well available in practice

Strongly dependent on reg. circumstances



FCH forklift fleets require only one central refuelling station with minimal space occupancy



Battery-powered forklift fleets depend on several charging facilities requiring larger warehouse spaces

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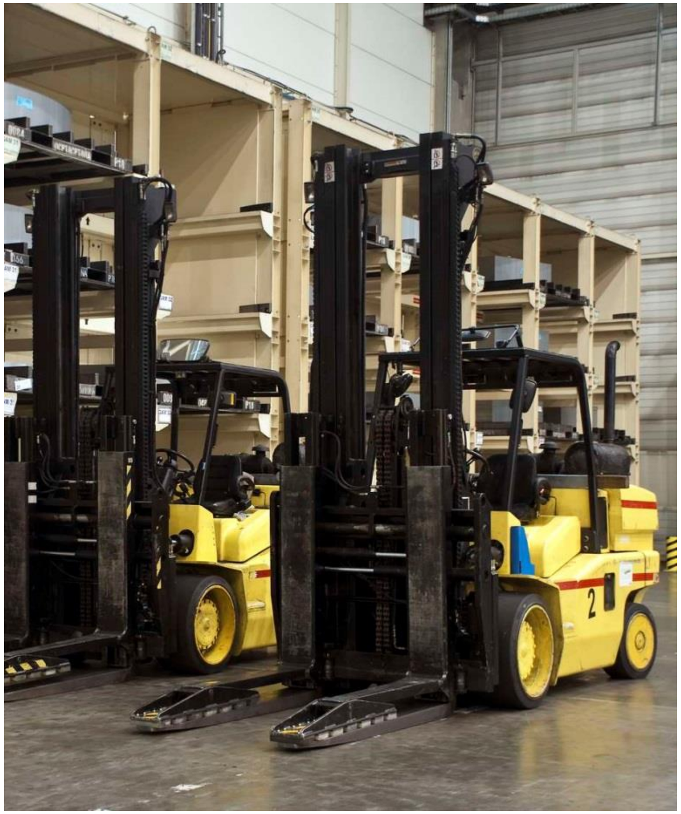
1) One potential future scenario combining alterations of different variables (each considered to be generally achievable by industry experts)

Source: Industry publications, FCH2 JU, Roland Berger

FCH forklifts typically feature higher availability and vehicle productivity than battery-powered competitors

Application-related assumptions

CURRENT / POTENTIAL[1]	**FCH Forklifts**	**Battery Forklifts**
Key technical specifications	Unit fleet size: 100 Refuelling time: 2.5 min Availability: *slightly higher (incl. refuelling time)*	Unit fleet size: 106 Changing time: 25 min Availability: *slightly lower (incl. refuelling time)*
CAPEX [EUR]		
Average full truck price	~ 35,000 / *~ 30,000*	~ 20,000 (incl. 2 batteries)
Replacements	-	~ 10,000
Refuelling[2]/changing station	~ 1,500,000 / *~ 1,200,000*	~ 950,000
Fuel		
Fuel type	Hydrogen (350 bar)	Electricity
Average fuel consumption (per h)	~ 0.15 kg / *~ 0.10 kg*	~ 3.0-4.0 kW
Maintenance costs [EUR]		
Forklift (per h)	~ 0.30	~ 0.67
Refuelling/changing station (p.a.)	~ 65,000 / *~45,000*	~ 35,000
Add. labour costs [EUR]		
Refuelling personnel p.a.	-	~ 205,000



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1) One potential future scenario combining alterations of different variables (each considered generally achievable by industry experts)
2) Assuming a daily refuelling capacity of ~500 kg/d to allow fleet increases in the future, i.e. a larger capacity than for the ~320 kg/d needed for this initial fleet

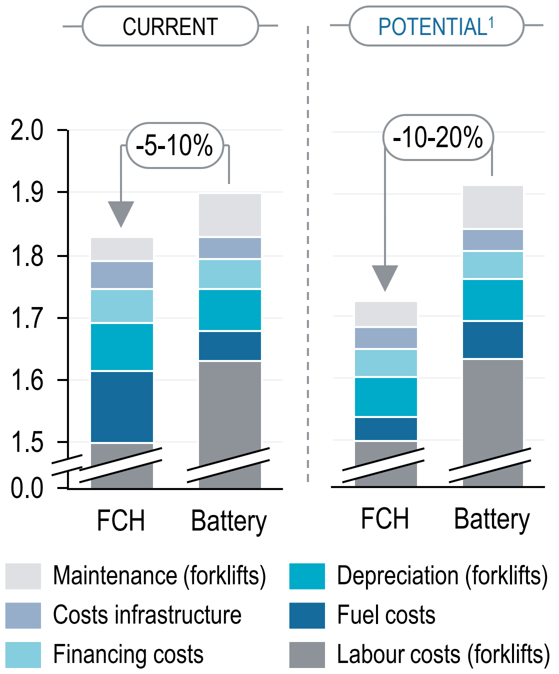
Source: Industry publications, FCH2 JU, Roland Berger

Since FCH forklifts display lower total cost of ownership than their battery counterfactuals, they are already fully commercialized

Business case and performance overview – INDICATIVE EXAMPLE

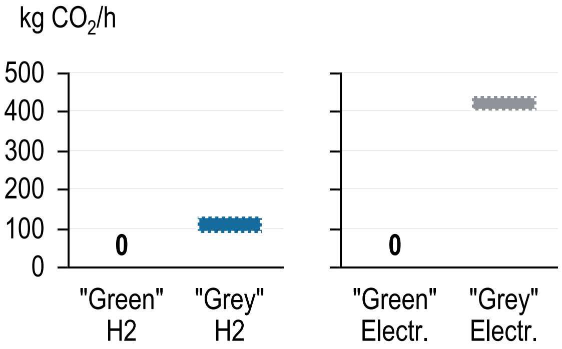
Economic

Estimated annualised Total Cost of Ownership (TCO) [kEUR/service hour]



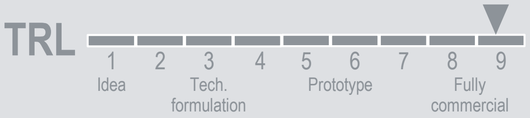
Environmental

- Zero tailpipe (i.e. tank-to-wheel) emissions of CO_2, pollutants such as NO_X and fine dust particles for FCH forklifts – key benefit for personnel on site as well as outside environment
- Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and vehicle efficiency (i.e. fuel consumption) – **potential for zero well-to-wheel emissions for FCH forklifts with "green hydrogen"**



Technical/operational

- **High technical maturity** of fuel cell technology to be used in forklifts – one of the most advanced FCH applications overall
- Hence, FCH forklifts are **already fully commercialized** with >10,000 fuel cell powered forklifts in operation or in order globally
- Functionality proven through long-term usage in real live environments
- Commercial users including multinational companies such as BMW, Daimler, Walmart, Amazon and Carrefour have deployed large fleets already



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1) The "POTENTIAL" scenario requires a number of FCE-related and other factors to fall in place in the medium/long run (please see previous slide)

Source: FCH2 JU, Roland Berger

The impact of TCO drivers varies, creating several levers for further reduction of hydrogen TCO compared to battery TCO

Key determinants of the business case[1] – INDICATIVE EXAMPLE

Important sensitivities considered…

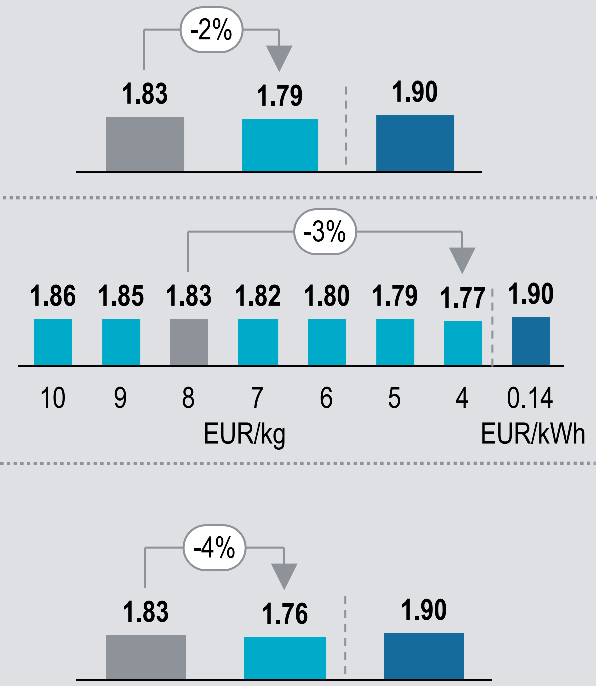
1 **Fuel cell forklift fuel consumption:** reducing the fuel consumption of the FCH forklift to 0.1 kg H_2/h results in an overall reduction of costs per service hour of EUR ~4 ct

2 **Fuel costs:** a price reduction for hydrogen to EUR 4 per kg H_2 potentially further strengthens the viability of the business case by reducing overall costs per service hour by EUR ~6 ct – **strong regional differences**

3 **3-shift operating model:** increasing the operating hours per day to a 3-shift model reduces CAPEX costs – this results in a cost reduction per service hour of EUR ~7 ct – **strongly dependent on the effect of maintenance costs and fuel cell stack/battery replacement**

… estimated impact on TCO

['000 EUR / service hour]



▨ FC Forklift TCO, base case 🟦 FC Forklift TCO, adjusted variables ■ BE Forklift TCO, base case

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1) Unless otherwise stated, all statements shall be considered as 2017-based and *ceteris paribus*, i.e. "all other things equal"

Source: FCH2 JU, Roland Berger

When identifying suitable use cases, regions and cities should look for large fleets of FCH forklift trucks operating in several shifts

Key characteristics of promising use cases for FCH forklift trucks

Multi-shift operations: 2 or 3 shifts over 6 to 7 days every week over the course of the year – thus constantly high availability requirements for material handling

Sizeable fleets: several dozens, >50 or even >100 forklift trucks with corresponding infrastructure requirements, e.g. in larger high-throughput food distribution centres, consumer and retail distribution centres, large factories, etc.

Affordable hydrogen supply (esp. relative to electricity supply costs): e.g. hydrogen that is obtainable from low-cost on-site generation in close proximity

High battery changeover costs: hence significant savings from (labour) productivity gains (in environments with comparatively high labour cost

Source: FCH2 JU, Roland Berger

B.7 Bikes

Fuel cell bikes are a highly flexible medium range option for public transport with a variety of potential use cases

Value propositions of fuel cell hydrogen bikes

High daily ranges

… of up to 100 km without refuelling

Variety of use cases

… e.g. for (postal) delivery fleets, public and private tourism, bike renting/sharing

Low entry barriers

… due to low CAPEX requirements for bikes and infrastructure compared to fossil fuel motorization

Fast refuelling

… less than 1 min per bike possible – several refuelling cycles per day possible

High visibility

… due to mobility and direct interaction of citizens with H_2 technology

Close to full technological maturity

… with several companies commercially offering FCH bikes and the respective infrastructure

Source: FCH2 JU, Roland Berger

We considered the touristic deployment of 20 new bikes from one station, covering a typical distance of ~50 km per bike and day

Use case assumptions and exogenous factors – SIMPLIFIED

Use case

> **Tourism operator** offering his service **~90 days** a year, plans to provide **sight-seeing tours** on FCH/BE bikes. The operator therefore considers the deployment of **~20 new** FCH/BE bikes, with **~50 km** of distance covered on average per operational day and bike, resulting in annually **~4,500 km** per bike

> The HRS for FCH bikes consists of an **on site electrolyser**, producing up to **0.5 kg H_2 per day**

> The charging of the batteries for the BE bikes takes place at the depot and includes a central transformer and cable charging infrastructure for BE bikes

Exogenous factors

> Financing costs for bike operator: 5% p.a.

> Cost of electricity: 0.21 EUR/kWh

Strongly dependent on specific regional circumstances

Source: FCH2 JU, Roland Berger

Within our analysis we benchmark FC with BE bikes in a current use case scenario, partially also depicting future potential of FC bikes

Application-related assumptions – SIMPLIFIED

CURRENT / POTENTIAL	**FCE bike**	**BE bike**
Technical specifications		
Infrastructure	FCH on site electrolysis	Overnight charging
Weight (kg)	25 kg	20-25 kg
Max. operating distance (km)	~100	~50-100
CAPEX (EUR)		
Purchase price (bike)	7,500 / 3,500	4,000
Refuelling station	150,000 / 90,000	10,000
Fuel		
Fuel type	Hydrogen (200 bar[2])	Electricity
Consumption (per 100 km)	~35 g	~0.7 kWh
Maintenance costs (EUR)		
Bike per year	250	250
Refuelling station p.a.	~8,000	~500
Replacements[1] (EUR per unit)	-	~800 (per battery)

[1] Additional battery pack per bicycle due to extended charging time and limited action range
[2] Pressure of tanks increasable, resulting in higher operating distances

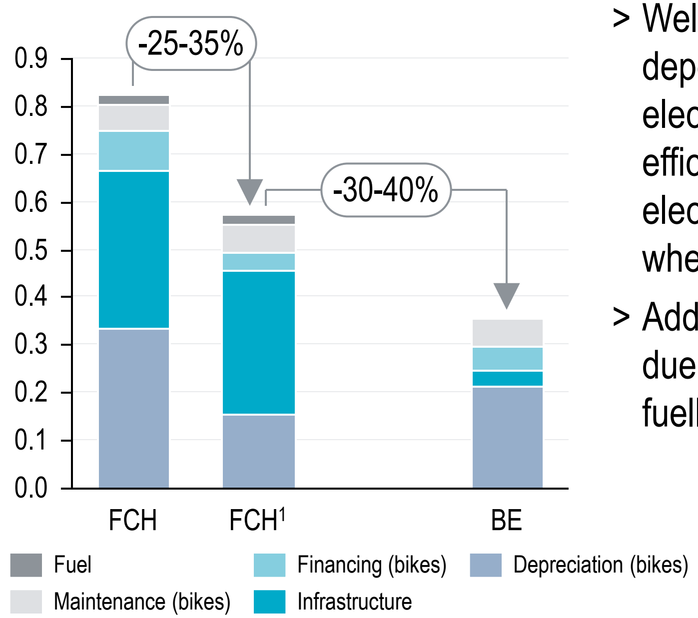
Source: FCH2 JU, Roland Berger

FCH bikes offer a 0-emission transport app. with a cost premium that has the potential to decrease significantly in the medium run

Business case and performance overview – INDICATIVE

Economic

Total Cost of Ownership [EUR/km], annualised at 2017 prices

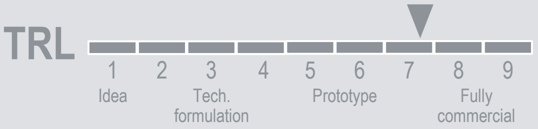


Environmental

- > Zero tailpipe emissions of CO_2, pollutants (NO_X, SO_x) and fine dust particles
- > Well-to-wheel CO_2 emissions depend on fuel source (source of H_2, electricity mix, etc.) and vehicle efficiency, green H_2 or 100% green electricity would reduce well-to-wheel CO_2 emissions to zero
- > Additional potential emission savings due to switching from other fossil fuelled transportation to FCH bikes

Technical/operational

- > Fuel cell electric bikes are generally still in the advanced prototype phase but first demonstration projects, larger field tests as well as first commercial projects are ongoing (esp. in FR)
- > FCH bikes have an operating range of up to 100 km
- > Fast refuelling times of <1 min per bike vs. BE bikes up to 7 hours



1) The potential scenario is partially based on economies of scale, especially affecting the price per bike as well as the infrastructure costs

Source: FCH2 JU, Roland Berger

B.8 Scooters

Many potential use cases for FC scooters can be identified, supported by the operational characteristics of FCH scooters

Use case characteristics

Description

> **A variety of real-life application cases for FC-electric scooters** exist:
- Police patrolling
- Delivery and postal services
- Scooter-sharing
- Staff mobility
- ...

> Depending on the application case, a typical operator would deploy **~10-100 FC-electric scooters**

> Refueling of FC-electric scooters takes place at **public refueling stations** or at **company-owned depots**

> FC-electric scooters will be able to **enter inner-city environmental zones** and hence provide operators with a competitive edge in comparison to conventional combustion-engine scooters

Technical facts[1] & competing technologies

	FCH scooter	BE scooter
Propulsion	2.5 – 12 kW	~2.5 kW / 60V 30AH battery
Range	150 – 250 km	<100 km
Max. speed	60 – 70 km/h	50 – 60 km/h
Refuelling time	<1 minute	~4 – 8 hours

Alternative technologies include: conventional fossil-fuel powered scooters and LNG scooters

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[1] The technical characteristics for FCH scooters as well as BE scooters strongly vary depending on specific use case and product/prototype under consideration

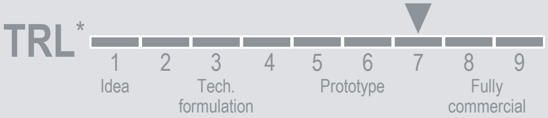
Source: Industry publications, Suzuki, FCH2 JU, Roland Berger

Despite being in the prototyping phase, Suzuki FC scooters were the first FC vehicle to receive a mass production license

Business case and performance overview – INDICATIVE

Technical/operational

- FC scooters commonly display **a hybrid set-up, combining a battery power source with fuel cells** – they can be classified as FC-electric scooters
- FC-electric scooters are still in the **prototyping phase** – however, Suzuki Burgman FC scooters were the **first FC vehicle to receive a "Whole Vehicle Type Approval" (WVTA**) in the EU
- They display **favorable range and refueling times** compared to battery-electric scooters
- **Challenge:** Lack of refueling infrastructure is inhibiting a widespread market introduction



Economic

- **Higher system efficiency,** lower maintenance and operating costs are counterbalancing relatively higher CAPEX costs in comparison to conventional combustion-engine scooters
- FC-electric scooters are zero-emission vehicles, thereby **enabling companies to operate inside environment-zones** or **zero-emission zones**
- **Key business case drivers**:
  - Cost of hydrogen vs. cost of diesel
  - System CAPEX
  - Cost of infrastructure (strongly dependent on whether public refueling stations or a private depot infrastructure will be used)

Environmental

- **Zero tailpipe (i.e. tank-to-wheel) emissions** of CO_2, pollutants such as NO_X and fine dust particles as well as significant noise reduction for FC-electric scooters – key benefit for drivers as well as outside environment
- Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-wheel emissions for FC-electric scooters with "green hydrogen"**

*) Technology Readiness Level

Source: FCH2 JU, Roland Berger

Public FC scooter deployments will increase awareness, thereby kick-starting commercialization

To be validated by demo projects

Key considerations concerning FC-electric scooters

- **Demonstration projects initiated by public authorities** will kick-start the deployment of FC-electric scooters by increasing public awareness and improving the public's perception regarding FC-electric scooters (see real life FC scooter trials "London Metropolitan Police ")
- **Technical characteristics and resulting operating possibilities**, including range and refuelling time, exceed the potential of other competing technologies e.g. BE scooter
- **Incurring costs, fuel supply logistics** and **proficient maintenance personnel** are among the major **hurdles** faced by operators interested in FC-electric scooters
- **Public hydrogen infrastructure** needs to be expanded to accelerate the deployment of FC-electric scooters and improve company-internal TCO calculations
- **Authorities place increasing importance on decarbonisation and emissions reduction** and will hence stimulate the development of zero-emission vehicles
  - The establishment of **inner-city environmental-zones further benefits the FC-electric scooter deployment** by offering companies using emission free vehicles (e.g. FC-powered) exclusive access to city-centers

Source: FCH2 JU, Roland Berger

C. WG3: "Maritime and aviation transport applications"

Maritime and aviation applications are mostly in conceptual or prototyping stages – First demonstrations are deployed

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
Ferguson marine
SEMA consulting

Source: FCH2 JU, Roland Berger

C

Each analysis consist of 3 key elements (use case, technologies, performance) – Regional differences will be tackled in Phase 2

Prel. business case components and flow of analysis – SCHEMATIC

Exogenous assumptions, e.g. energy/fuel cost, carbon intensities

FCH application

- Technical features (e.g. output, efficiency, lifetime, fuelling requirements) and general readiness
- Est. CAPEX / system cost
- Est. OPEX (e.g. maintenance)

… plus benchmarking against competing technologies

1 "generic" use case

…consisting of typical deployment requirements of European regions and cities

Basic performance

- Technical / operational
- Economic
- Environmental

Source: FCH2 JU, Roland Berger

C.1 Ferries

Use case and applications determine capital, fuel, O&M and infrastructure cost that in turn make up the operator's TCO

Key elements of FCH maritime applications' TCO – SCHEMATIC, SIMPLIFIED

Operator's perspective …

The task / scenario at hand: use case, deployment context, target operating model, e.g.

- Route definition and length
- Target capacity
- Target roundtrip-time, target schedule for operations
- Target availability
- Oceanographic and meteorological conditions
- Fleet size
- Energy cost
- Carbon intensities
- …

FCH vessel / system specifications and performance

- Volume, weight, etc.
- Maximum / cruising speed
- Powertrain design, e.g. power output of fuel cell
- Fuel cell technology
- Efficiency / fuel consumption
- Hydrogen storage system
- Degradation
- Lifetime
- Availability
- …

Hydrogen infrastructure specifications and performance – sharing ratios

1. Capital cost

- Investment / depreciation,
- Financing cost

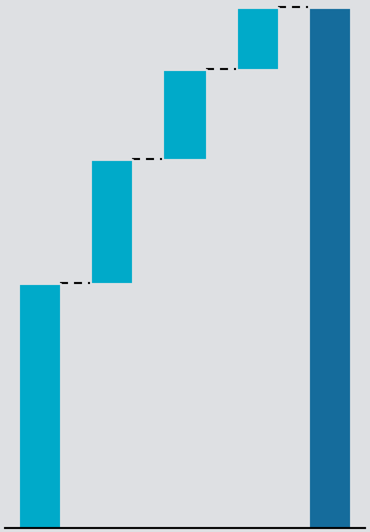
2. Fuel cost – H_2 consumption, H_2 price (dep. on production, distribution, volumes, input prices, etc.)

3. Other O&M cost, e.g. for vessel maintenance, personnel, utilities, fees/levies, taxes[1]

4. Infrastructure cost

- Investment / depreciation
- O&M cost

Total Cost of Ownership (TCO) in EUR p.a. or EUR/nm



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[1] Largely excluded for preliminary business case analysis, more detailed consideration in Project Phase 2

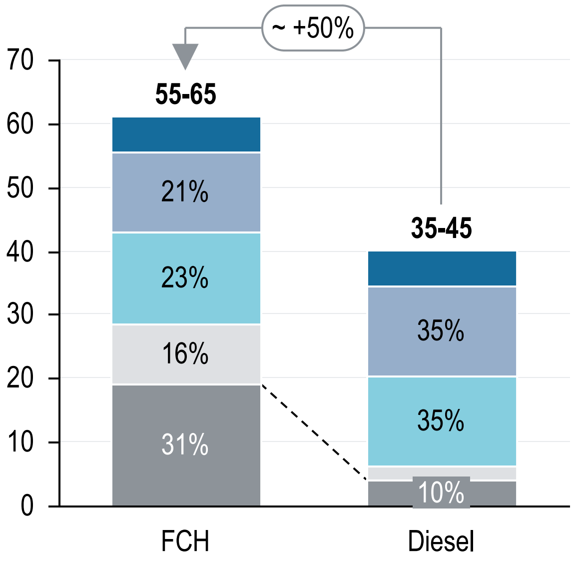
Source: FCH2 JU, Roland Berger

An initial FCH ferry would likely yield a significant cost premium over a diesel ferry – significant CO_2 savings expected, esp. with green H_2

Business case and performance overview – INDICATIVE

Economic[1]

Estimated annualised Total Cost of Ownership [EUR/nm]

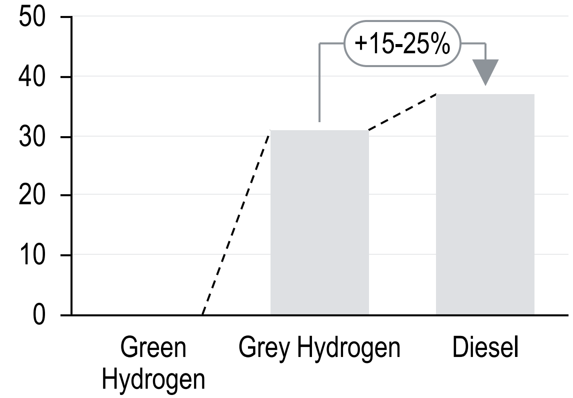


- 🟦 Maintenance costs
- 🟦 Fuel costs
- 🟦 Labour costs
- ⬜ Financing costs
- ⬛ Depreciation (ferry & infra.)

Environmental[1]

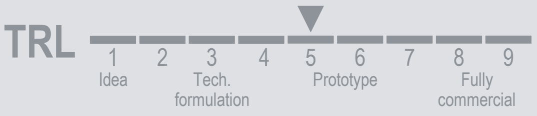
- Zero local emissions of CO_2, pollutants such as NOx, fine dust particles when using green hydrogen
- CO_2 emissions well to wheel dep. on fuel source and fuel efficiency; in this example, a green hydrogen fuel cell ferry saves nearly 1,250 t CO_2 p.a. – comparison of CO_2 emissions

[kg CO_2/nm]



Technical/operational

- Pure FCH electric ferries are currently in a development phase, first pilot demonstration projects with prototypes will be starting within the next 5 years
- Medium-term commercialisation unlikely, initial priorities are successful demonstration projects in areas with high need for decarbonisation of maritime public transport, e.g. Scandinavia, Mediterranean
- Challenges: initial regulatory framework and permitting (e.g. refuelling protocols, FCH powertrain for maritime appl.), hydrogen supply (quantities, cost efficiency)
- Potential to meet same operational requirements (range, refuelling time) – like diesel/MGO ferries



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1) Initial rough estimate based on concept work on a high-speed passenger ferry for daily public transport in Northern European coastal waters (see following slides)

Source: FCH2 JU, Roland Berger

CAPEX of ferry and infrastructure as well as cost of hydrogen are key determinants for the business case at hand

Key sensitivities and assumptions for this use case – INDICATIVE

> **Capital cost of FCH ferry and hydrogen infrastructure:**

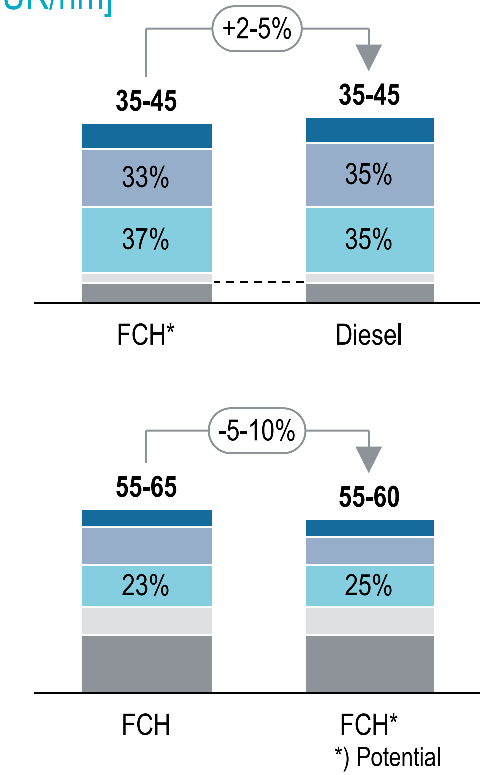
- Highly dependent on the **technical specifications** which in turn derive from the **deployment use case** (capacity, route length, target roundtrip-time, oceanographic and meteorological conditions, etc. determine necessary maxima of cruising speed, power range, operating model and efficiency of fuel cells) **– strong regional differences**; initial costs for development, testing and permitting/certification as well as cost of refuelling infrastructure (as attributed) are decisive factors
- Here: If capital cost of ferry and refuelling infrastructure were reduced to diesel levels, TCO would fall below diesel levels (all other things equal)

> **Hydrogen supply and cost of hydrogen:**

- Relatively **high volumes of hydrogen consumption** (e.g. here nearly 400 kg per day and vessel) require large supplies, storage and refuelling capacities – supplying green hydrogen from large-scale electrolysis with cheap renewable electricity might be the ideal long-term solution
- Here: Reducing the price of hydrogen to 2.50 EUR/kg leads to a reduction in TCO of 2-5 EUR/nm (or -5-10%) **– strong regional differences**

Estimated TCO impact

[EUR/nm]



*) Potential

🟦 Maintenance costs 🟦 Fuel costs 🟦 Labour costs ⬜ Financing costs ⬛ Depreciation (ferry & infra.)

Source: FCH2 JU, Roland Berger

For analytical purposes, we consider a hypothetical ferry use case in Europe based on interviews with industry experts

Preliminary business case components and key assumptions

Applications and technologies

initial deployment	**FCH Ferry**	**Diesel Ferry**
Technical data		
-- Ferry length	30 m	30 m
-- Passengers	100	100
-- Powertrain	2 x 800 KW PEM FC	2 x 800 KW Diesel Eng.
Lifetime	25 years	25 years
CAPEX[1]	~ EUR 11-15 m	~ EUR 3-3.5 m
Fuel	Hydrogen (250 bar[2])	Diesel
Fuel consumption	3.4 kg/nm	14 l/nm
Maintenance	2.76 EUR/nm	2.53 EUR/nm
Infrastructure	HRS	RS
-- CAPEX	3,000,000 EUR	345,000 EUR
-- OPEX	100,000 EUR/y	100,000 EUR/y

Use case and exogenous factors

Strongly dependent on reg. circumstances

- Starting in 2021, a fuel cell powered passenger ferry will offer daily public transportation between to cities along the costal line of a European province with ~100,000 inhabitants
- With a top speed of ~28 kn and average speed of ~22 kn, the ferry will offer 360 round trips à 115 nm per year, requiring one (overnight) refuelling at the home port
- Resulting annual operations in this use case:
  - Total annual distance travelled: ~ 33,800 nm
  - Annual energy requirements: ~1,870,000 kWh (~6,300 kWh/d)
  - Annual hydrogen consumption: ~122,500 kg (~390 kg/d)

Strongly dependent on reg. circumstances

- Source of hydrogen: electrolysis from (low-cost) hydropower
- Cost of hydrogen: 3.5 EUR/kg
- H_2 refuelling infrastructure: one refuelling station at the home port, synergies with other port-related FCH applications (e.g. forklift trucks)
- Cost of Diesel: 1.01 EUR/l
- CO_2 footprints of green / grey hydrogen : 0 / 9 kg CO_2/kg
- CO_2 footprints of diesel : 2.64 kg CO_2/l
- NO_X footprints of diesel: 0.004 g/l

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1) Incl. cost of initial development, testing, permitting/licensing/approvals (excl. possibly necessary fuel cell stack replacements)

2) Alternative tanks pressure between 200 -700 bar

Source: FCH2 JU, Roland Berger

C.2 Boats

Two possible application cases exist for smaller fuel cell boats – pleasure boats and commercial passenger boats

Possible use cases for FCH boats

INDICATIVE

	1 **Pleasure boats**	2 **Commercial passenger boats**
		
Description	Small boats for private usage, either sold directly to end-customers as pleasure boats or sold to boat rental companies	Smaller excursion boats to be used for sightseeing and other touristic/recreational activities on (urban or other inland) waterways, e.g. canal and river sightseeing tours
Type of boat		
- Size	Length: ~4-10 m, width: ~1.5-3 m	Length ~15-25 m, Width ~3-6 m
- Passengers	n.i.	~60-100 passengers
- Output	~2-6 kW fuel cell, ~50-90 km range	~50-100 kW fuel cell, ~8-12 hour range
Competing Technologies	Diesel, CNG, battery-electric, possibly solar-powered	Diesel, CNG, battery-electric

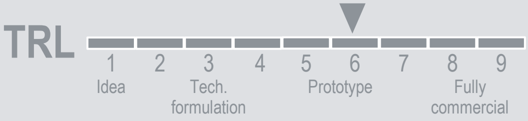
Source: FCH2 JU, Roland Berger, Fronuis, Simplyamsterdam, Rijksdienst voor Ondernemend Nederland

FC boats are not commercialized yet, but short refuelling times and zero local emissions emphasize their future potential

Business case and performance overview – INDICATIVE

Technical/operational

- Advanced **prototype stage**, albeit very **diverse product segment** with 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**
- **In principle, similar operational characteristics to be expected as diesel-combustion boats** (e.g. refuelling times, flexibility, ranges)



Economic

- **Higher system efficiency**, lower maintenance and operating costs are counterbalancing relatively higher capital costs of FC boat vs. conventional powertrains
- **Short refuelling times** and long ranges increase availability rates in comparison to battery-electric boats and hence improve the profitability of (battery-electric) boat rental companies
- **Key business case drivers**:
  - Cost of hydrogen vs. cost of diesel/electricity
  - Boat CAPEX
  - Infrastructure costs, esp. refuelling station CAPEX (incl. utilisation) and OPEX

Environmental

- **Zero tailpipe (i.e. tank-to-wheel) emissions** of CO_2, pollutants such as NO_X and fine dust particles for FCH boats as well as significant reduction of noise and vibrations – key benefits for passengers on board as well as outside environment
- **Lower noise emissions as key benefit for inland waterways**, esp. in urban environments
- Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-wheel emissions for FCH boats with "green hydrogen"**

*) Technology Readiness Level

Source: FCH2 JU, Roland Berger

When identifying suitable use cases, Regions & Cities should look into the private and the commercial sector and leverage synergies

Key considerations concerning fuel cell boats

- **Increasing emphasize on decarbonisation, emissions reduction and water protection** is stimulating the development of zero-emission engines such as fuel cells for pleasure boats and small passenger boats
  - Already today, national legislations **ban combustion engines** on several environmentally **sensitive lakes,** urban waterways (e.g. canals) will be increasingly affected by local emission regulations as well
  - **Boat rental companies and commercial passengers boats** will also be affected by **supranational regulations** on EU-level such as CO_2 monitoring requirements as well as cap and trade policies
- **Capital cost and fuel supply** are among the major **hurdles** faced by fuel cell powered boats – a sufficiently extensive hydrogen **infrastructure available to commercial and private users** needs to be established
- **Gaps in the regulatory framework and industry standards need to be closed**, e.g. regarding the use of gaseous hydrogen on boats or refuelling protocols
- Further **demonstration projects** will be necessary to **increase technological readiness and hence commercial availability**

Source: Roland Berger

C.3 Ships

The shipping industry is very diverse, likely requiring highly customized FCH power solutions for each use case

Key dimensions for potential FCH power solutions for large vessels – SIMPLIFIED

Type of vessel

- Container ship
- Tankers
- Short sea shipping
- *Cruise ships*
- Ferries
- Yachts
- Navy ships
- Icebreakers
- Tugs
- Submarine

Application purpose

- Full powertrain for propulsion and on-board energy supply (e.g. for (in-port) hotel services on cruise ships)
- *Separate on-board power supply*

Relevant FC technologies

- Low-temperature PEM FC
- High-temperature PEM FC
- Solid-Oxide FC (SOFC)

Dimensions of FC applications for ships

Available fuels

- Pure hydrogen (liquid / gaseous)
- Hydrocarbon compounds (with on-board reforming): Methanol, Diesel, Marine Gas Oil (MGO), Liquefied Natural Gas (LNG)

Refuelling options

- *Initial fuelling at the port and on-board bunkering*
- Direct on-shore energy supply provided by every port
- Fuel/power supplied in port through pipelines, trucks or barges

Other dimensions

- *to be discussed*
- …

To be considered in the exemplary use case on slide 8

Source: FCH2 JU, Roland Berger

Additionally, potential fuel cell application cases are very much dependent on vessel-specific energy requirements

Energy consumption of different types of vessels during lay time in port

Vessel Type	Power Required [in kW]			Run Time [in h]		
	Typical	Low	High	Typical	Low	High
Harbor Tug	100	7.5	410	4	1	6
Fishing Trawler	200	75	670	contin.	48	months
Bulk	200	150	300	48	-	-
Tanker (steam pumps)	700	550	800	48	24	72
Auto/RoRo	800	700	890	24	24	36
Container	1,400	500	8,400	48	24	72
Reefer	3,000	900	5,600	60	48	72
Cruise ships	**6,000**	**3,500**	**11,000**	**10**	**10**	**12**
Tanker (elec. pumps)	7,800	-	-	48	24	72

Implications

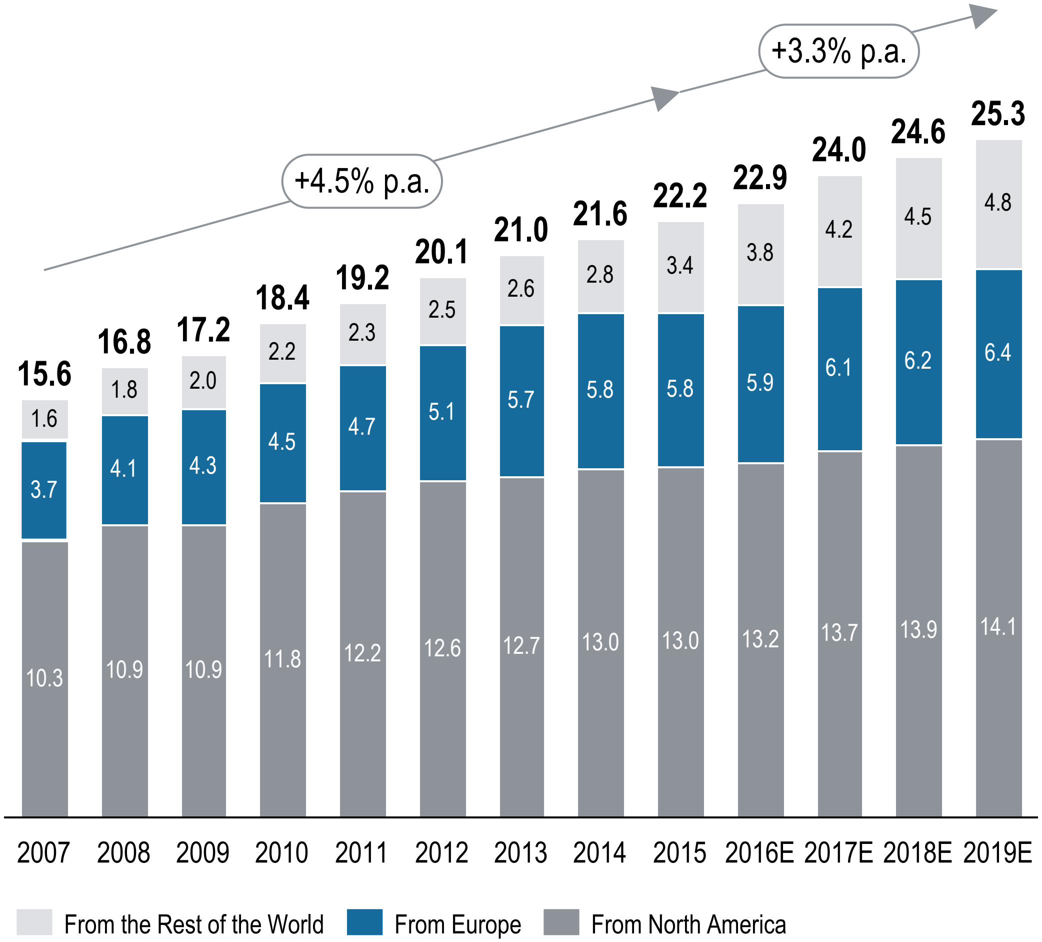
- There is a **great variety of energy requirements** among different types of vessels, resulting in **different application cases for FC technology**
- **Cruise ships** display among the **highest energy** requirements and will hence be **affected by EU / IMO requirements on emission restrictions more drastically**
- **Autonomous, crew-less ships** might **reduce power requirements in the future**, making energy-demanding applications such as A/C and heating obsolete

Exemplary focus on the following slides

Source: Port of Valencia, FCH2 JU, Roland Berger

One example for a use case: energy supply for cruise ships – serving to a growing market with continuously increasing emissions

Cruise passengers per source region [m passengers; 2007-19E]



CAGR 07-15	CAGR 15-19E
10.1%	8.8%
5.6%	2.5%
3.0%	2.0%

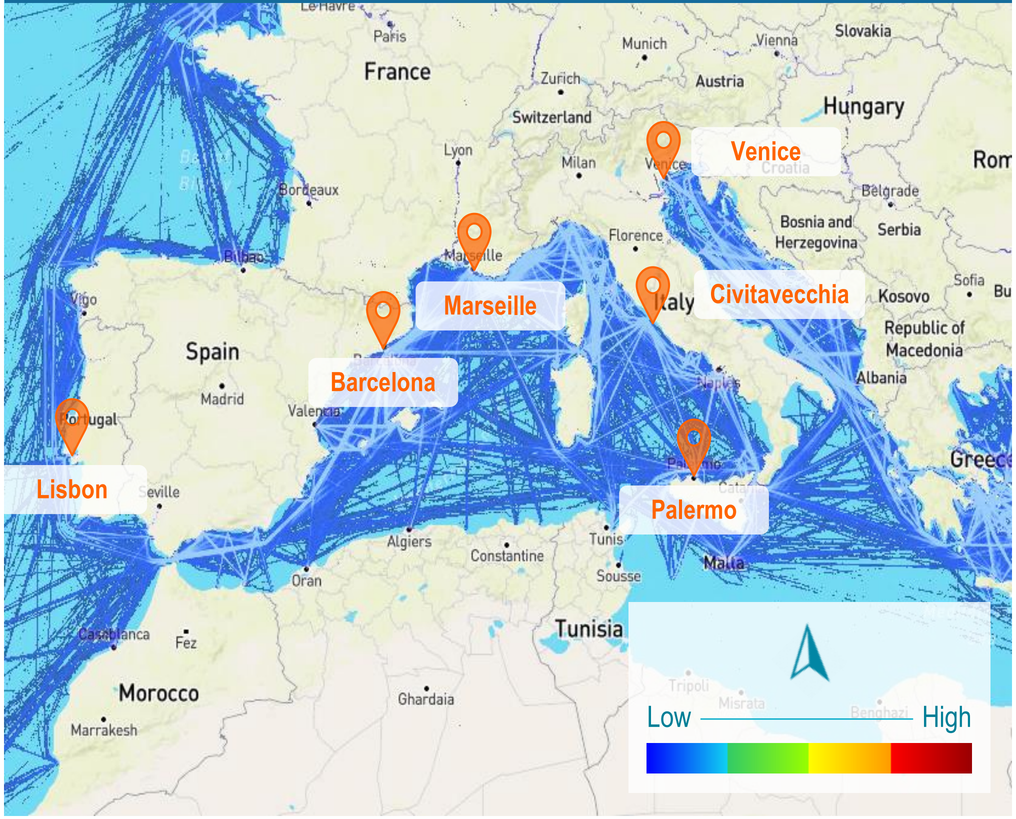
- **Cruise passengers should grow +3.3% p.a.** from 2015 until 2019
- **Economic recovery from the 2009 crisis and growth of emerging cruising regions** such as Asia or the Middle-East should drive cruise demand
- Markets such as **China and Australia** grew by **40.3% and 14.6% in 2015 alone**
- **The United States' cruise penetration rate has only risen slightly** in recent years from 3.3% in 2011 to 3.5% in 2015
- **Globally, total emissions of greenhouse gases, pollutants and fine dust particles from cruise ships are increasing**

Source: Cruise Market Watch, CLIA, FCH2 JU, Roland Berger

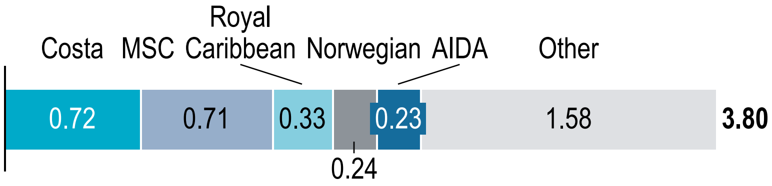
Popular ports and routes will be disproportionately affected by increasing passenger numbers and resulting emissions

One example: Mediterranean cruise market

Maritime route tracking map [passenger vessels]



Top players [million passengers; 2016]



Key market dynamics

> In 2015, the two largest ports in the Mediterranean were **Barcelona** and **Civitavecchia** with over **2 m cruise passenger movements** each and responsible for **9.3% and 8.3%** of total passenger movements

> **Civitavecchia** (major point of call for Rome) had the **largest number of calls** with 794, followed by the **Balearic Islands** at 788, **Barcelona** at 749

Source: MedCruise, Marine Traffic, Cruise Industry News, Press review, FCH2 JU, Roland Berger

Separate on-board engines for in-port hotel services powered by FC technology can drastically reduce emissions in cruise ship terminals

Context and use case of a typical cruise ship power supply application

Cities with inner-city cruise ship terminals are heavily affected by pollution (pollutants, fine-dust particles and greenhouse gases) from on-board energy supply during lay times

- With energy demands between 6 and 12 MW (the "hotel load") a large cruise ship (capacity of more than 3,000 passengers) with a lay time of ~10 h requires 60-120 MWh of energy supply for in-port hotel services
- If this energy demand is satisfied by using on-board combustion engines powered by fossil fuels (e.g. marine gas oil), 50-60 t of CO_2[1] are emitted into the atmosphere during this one stay, the equivalent of approx. 25-30 compact cars in 1 year
- As an alternative, different technological solutions are available to reduce emissions:
  - **On-shore energy** via the port: here, sufficient supply and grid infrastructure must be in place
  - **Separate on-board engines for in-port hotel services:** Different types of technologies are available, including the usage of small additional diesel/MGO powered engines and FCH applications

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1) Based on an energy demand of 9 MW

Source: FCH2 JU, Roland Berger, Hanseatic City of Hamburg, cruisemapper.com

In principle, in-port energy supply can be provided by on-board generators or onshore power supply

Benchmarking of energy supply technologies for in-port energy supply – SIMPLIFIED

	1 **Main propulsion engine**	2 **Separate generator – Diesel/LNG**	3 **Separate power supply – Fuel cell**	4 **Cold ironing (Shore-to-ship supply)**
				
Description	Energy supply generated by (parts of) main ship engines	Energy supplied by separate diesel engines only used for (in-port) hotel services, main engines switched off	Separate engine for (in-port) energy demand powered by fuel cell technology, main engines switched off	Power provided directly by port, all on-board engines switched off
Fuel	Diesel/MGO/LNG/...	Diesel/LNG/ …	Hydrogen/Methanol/LNG/...	Electricity
Maturity level	Operational & widespread	Operational & state-of-the-art	At conceptual stage	Operational & relatively rare
Important considerations	> Independent from port infrastructure > Reliable and controllable power supply > Usage of existing engines and fuel > Heavy in-port emissions of CO_2/ NO_X/SO_x/…	> Independent from port infrastructure > Reliable and controllable power supply > Reduced, but still significant CO_2/NO_X/… emissions due to tailored engine capacity and usage of cleaner fuels > Additional space and maintenance requirements	> Reliable and controllable power supply > Strong reduction or even elimination of CO_2/NO_X/… emissions > Additional space and maintenance requirements > Dependence on regular hydrogen/methanol/… supply in ports	> In-port emissions and noise eliminated > Port infrastructure/ sufficient power supply only available in ca. 10 major ports worldwide – voltage capacity to be extended > On-board power grid and connection to be adapted for external power supply

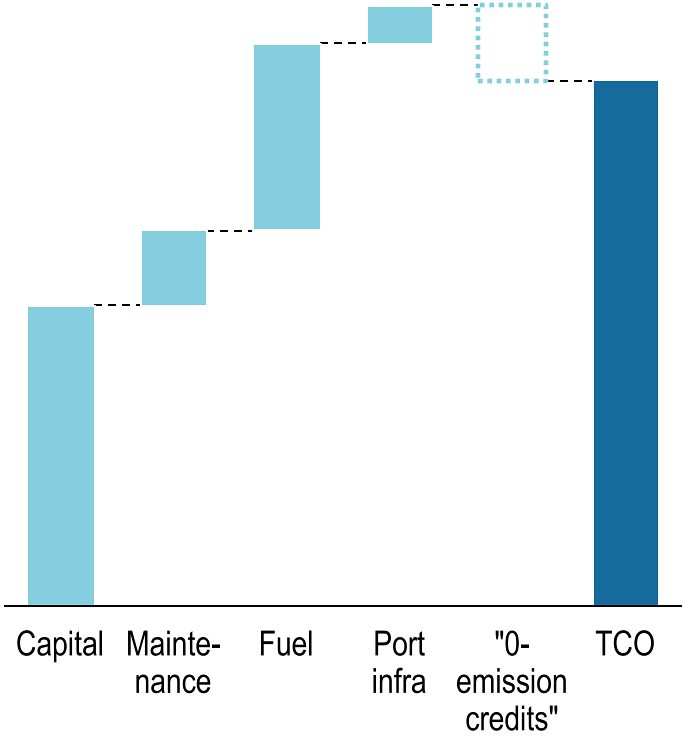
Source: FCH2 JU, Roland Berger, cruisemapper.com, designengineeringfaq.blogspot.de, motorship.com, stemmann.com

Total Cost of Ownership for FC marine power systems have common drivers but heavily depend on the individual application

Schematic outline of TCO for FC marine power systems and its drivers – SIMPLIFIED

Total Cost of Ownership (TCO)

(e.g. in EUR per port call)



Capital cost

- FC technology (i.e. LT PEM FC 1,900 – 2,300 €/kW)
- Power range (likely multi-MW)
- Fuel (& reforming), bunkering
- Durability / lifetime
- System integration

Maintenance cost

- Spare parts
- Labour and training
- Maintenance routine

Fuel cost

- Type of fuel and key input: electricity, natural gas
- Production and supply
- System efficiency (up to 60%$_{el}$, >90% $_{comb.}$)
- Fuel supply volumes and price

Port infrastructure cost

- Allocation of additional port refuelling infrastructure investments and expenditure to shipping companies

"0-emission credits"

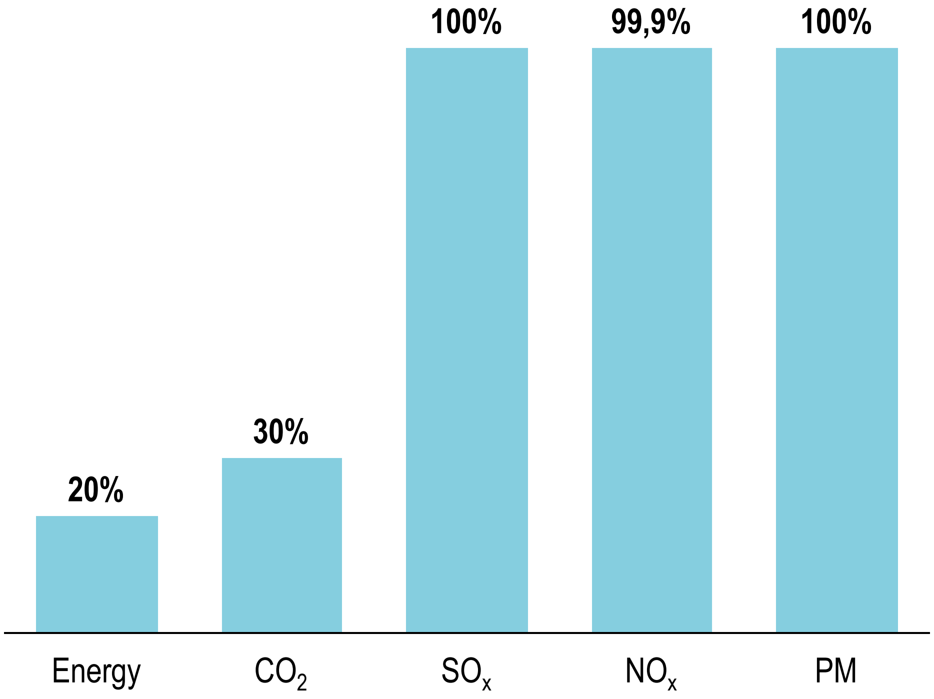
- Potential future policy measures to promote zero-emissions

Source: FCH2 JU, Roland Berger, Shell

Simulations show that fuel cells powered by low-carbon fuels can significantly reduce CO_2 and eliminate pollutant emissions

Environmental benchmarking of FC power systems vs. conventional systems

Potential energy and emission reductions of a typical cruise ship[1)]



Implications

- In comparison to a conventional diesel engine, **fuel cells powered by on-site reformed low-carbon fuels** lead to significant **reductions** in overall[2)] **emissions of CO_2, pollutants and fine dust particles**
- While **CO_2** can be **reduced by** approx. **30%, SO_x, NO_x,** and **PM** can almost be **eliminated**
- **Higher efficiencies** of fuel cells lead to reduced primary energy consumption of approximately 20%
- Please consult Joint Operation for Ultra Low Emission Shipping's conference documentation on HT PEM Fuel Cells for more information

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1) Based on a methanol-powered fuel cell in comparison to a conventional diesel engine; 2) Includes fuel production as well as port operations

Source: FCH2 JU, Roland Berger, e4 ships, Joint Operation for Ultra Low Emission Shipping

Decarbonisation is high on the agenda of cruise operators; FC power systems have to become part of the technology pool

Key considerations for looking at FC power systems for cruise operators

The **main drivers** to invest in alternative power supply systems is the increasing **importance to accelerate decarbonisation and other emission reductions**

- **Supranational regulations** from IMO- or EU-level will soon require CO_2 monitoring, cap and trade policies might be introduced in a second step
- **Stricter local emission regimes from port cities** will increasingly force aggressive curtailment of NO_x, SO_x and other pollutant emissions
- **Customer awareness** is growing as well – the emissions footprint of cruises becomes an increasing concern for clients

With operating times of 25 to 30 years per ship and lead times of 5 to 10 years before start of operations, the cruise ship industry has to adopt a **long term focus – FCH need to start become part of the technology pool soon in order to be part of the solution**

Necessary size /power ranges, capital cost and fuel supply are among the major **hurdles** FC power systems have to overcome

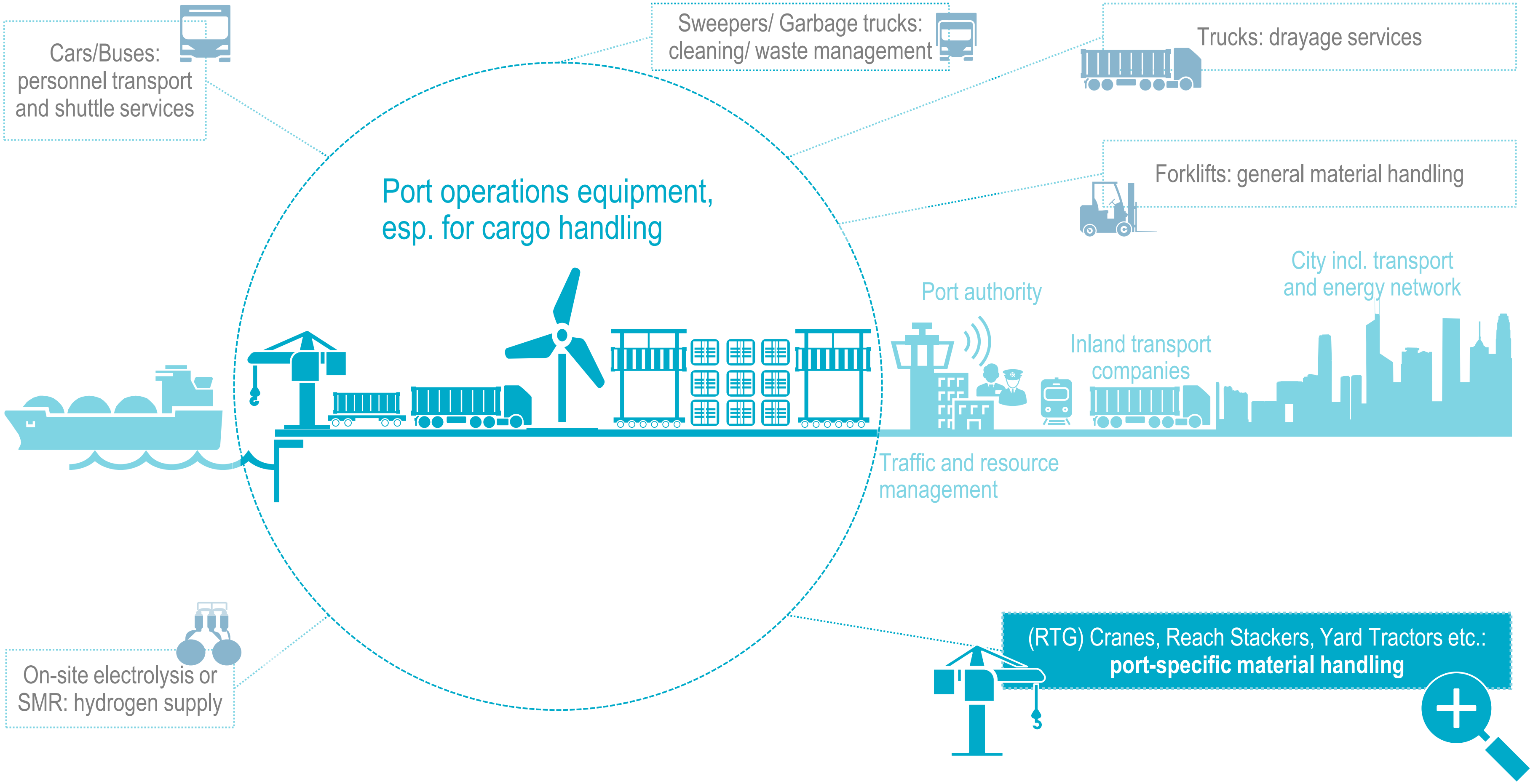
Operators need to trial new technologies (as they have trialled LNG as new fuel in the past) – a **demo FC vessels** can be used to **finalise permitting, certification and other frameworks**

Source: FCH2 JU, Roland Berger

C.4 Port operations equipment

Port operations are a complex ecosystem requiring multiple types of equipment – Manifold potential for FCH applications

Port operations ecosystem and FCH opportunities (selection)



Cars/Buses: personnel transport and shuttle services

Sweepers/ Garbage trucks: cleaning/ waste management

Trucks: drayage services

Forklifts: general material handling

Port operations equipment, esp. for cargo handling

Port authority

City incl. transport and energy network

Inland transport companies

Traffic and resource management

On-site electrolysis or SMR: hydrogen supply

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

Source: FCH2 JU, Roland Berger

RTG Cranes, Reach Stackers and Yard Tractors are the most important specific port operations equipment in this ecosystem

Port operations equipment (selection)

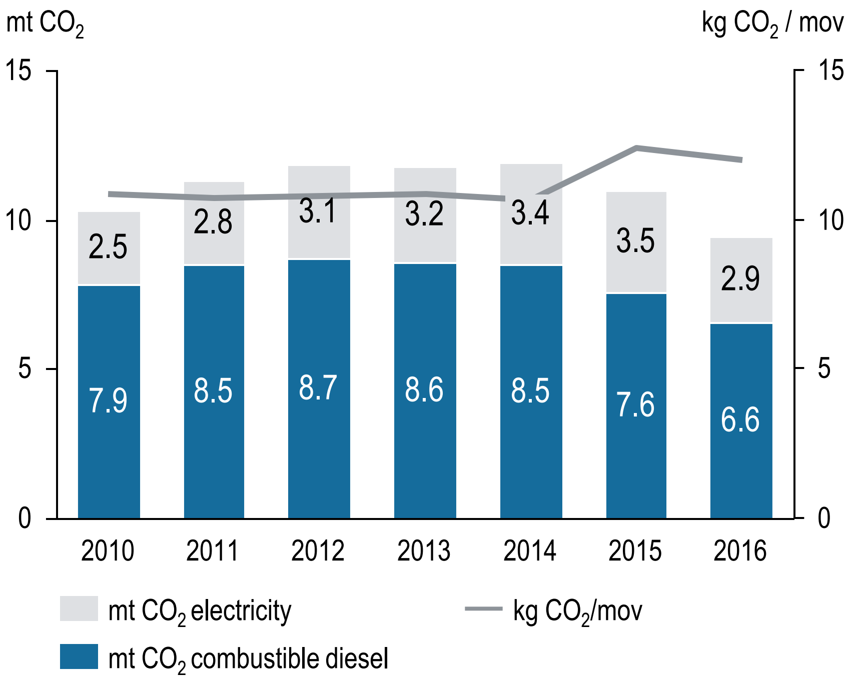
	RTG Cranes A	**Reach Stackers** B	**Yard Tractors** C
			
Brief description	Rubber Tyred Gantry (RTG) Cranes are mobile cranes which are used to ground or stack containers from yard tractors or drayage trucks and vice versa	Reach Stackers are used to handle containers and other cargo in ports; they are 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 (selection)	Liebherr, Kalmar, Konecranes, Sany	Liebherr, Kalmar, Konecranes, Sany, Hyster-Yale, Terex	Terberg, Kalmar, Orange EV
Engine / fuels	Diesel, electric (i.e. via a conductor bar), hybrid (diesel/battery-electric), LNG, CNG, biofuels	Diesel, hybrid (diesel/battery-electric), LNG, CNG, biofuels	Diesel, (battery-) electric, hybrid (diesel/battery-electric), LNG, CNG, biofuels

Source: FCH2 JU, Roland Berger

Collectively, they cause high CO_2 and noise emissions – the majority of emissions can be attributed to diesel-powered RTGs

Context and use case of a typical port operations terminal – EXEMPLARY

On-shore port operations are an important source of CO_2 emissions for port cities



- **CO_2 emissions of ports** can be attributed to electric and fuel powered applications[1]
  - **Fuel-powered yard machinery** (i.e. mainly diesel): RTGs (~60%), yard tractors (~35%), reach stackers and empty forklifts (~5%)
  - **Electric consumption:** Container reefers (~40%), STS cranes (~40%), yard lighting (~15%) and offices (~5%)
- In a **360,000 m² port terminal** with ca. 780,000 ship moves and 1.2 m TEUs, the collective energy demand causes **9.5 mt of CO_2** emissions per year, the equivalent of approx. 4,500 compact cars in 1 year
- Additionally, the **24/7 nonstop operating system** of ports negatively affects local residents due to **noise and pollutant emissions** like NO_X

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1) Percentages based on 2012 data provided by 'Port of Valencia'

Source: MSC Terminal Valencia, Port of Valencia, FCH2 JU, Roland Berger

Alternative energy supply technologies are available – Electric solutions and alternative fuels have great potential

Benchmarking of non-diesel options for port op's equipment – SELECTION

	1 **Battery electric**	2 **Electric conductor bar**	3 **LNG**	4 **FCH**
				
Emissions				
- *Well-to-Wheel*	- Dependent on electricity source	- Dependent on electricity source	- Moderate, lower than diesel	- Zero, if green hydrogen is used
- *Local*	- Zero	- Zero	- Low-moderate	- Zero
Technological readiness	Only diesel/battery hybrids commercially viable	Demonstration stage	Commercially available, early deployments ongoing	Development stage
In-port fuel availability	Available - Sufficient power supply might be problematic	Available – Sufficient power supply might be problematic	Increasingly available – LNG will likely be increasingly used to fuel ship engines in the future	Limited availability of hydrogen so far, regulatory requirements *TBD*
Infrastructure requirements	Multiple charging stations with associated space, grid and supply requirements	Expensive conductor bar network, grid and supply infrastructure	Refuelling stations attachable to the LNG ship refuelling system	Refuelling station and hydrogen supply solutions (pipelines/storage)
Fit with operational requirements	Long charging times are potentially challenging 24h (i.e. 24/7) port operations	Due to limited operational flexibility of conductor bar, hybrid vehicles with additional diesel engines might be necessary	Short refuelling times, 24h availability and flexibility provide a fit with operational requirements – albeit stick with emissions	Short refuelling times, long ranges, 24h availability and flexibility provide a good general fit with operational requirements

Source: FCH2 JU, Roland Berger, worldcargonews.com, portstrategy.com, lngworldnews.com, nuvera.com

FCH solutions can in principle satisfy a port operator's key needs – FCH prototypes and demonstration projects necessary

Key considerations for port operators in their technology choice – SELECTION

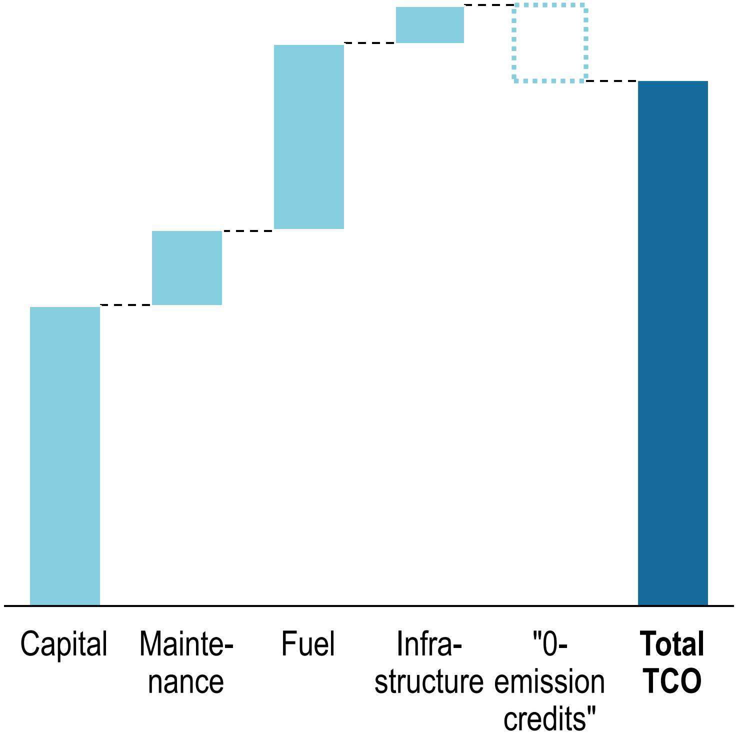
	High availability	High flexibility	Low / Zero emissions
Brief description	> **Tight scheduling** and **expensive delays** require high availability rates > **24/7 operating times** of ports minimize opportunities to counterbalance maintenance and downtimes	> **Complex container movement** and **storage strategies** (incl. efficient use of space and resulting constraints to manoeuvre) require port operating equipment with high operational flexibility	> Port cities are increasingly **challenged by emissions**, i.e. **CO_2 and noise** > 24/7 port operations can hence **significantly reduce life quality of local residents** within earshot
	Strict concern for Total Cost of Ownership (TCO)		**Regulation most relevant**
Opportunities & challenges of FCH applications	> **Short refuelling times** and **long ranges** fit port operator's requirements > **Lower availabilities** during **prototyping/ pre-commercial phases** can be covered by backup vehicles	> FC–powered equipment can **move flexible across the port terminal for several hours** (long range), before refuelling is necessary	> FCs **eliminate local emissions** such as CO_2, NO_X and **noise** entirely > **Green hydrogen supply** can reduce the carbon **footprint** to **zero**

Source: FCH2 JU, Roland Berger

Total Cost of Ownership for FC port operations have common drivers but will heavily depend on the individual ecosystem

Schematic outline of TCO for FC port operations and their drivers – SIMPLIFIED

Total Cost of Ownership (TCO)
(e.g. in EUR per TEU)



Capital cost

- FC technology (i.e. LT PEM FC 1,900 – 2,300 €/kW)
- Power range
- Fuel (& reforming), bunkering
- Durability / lifetime
- System integration

Maintenance cost

- Spare parts
- Labour and training
- Maintenance routine

Fuel cost – Cost of H2 vs. electricity, diesel, etc.

- Type of fuel and key input: electricity, natural gas
- Production and supply
- System efficiency (up to 60%$_{el}$, >90%$_{comb.}$)
- Fuel supply volumes and price

Refuelling infrastructure network costs

- Allocation of additional investments to cover costs associated with hydrogen supply

"0-emission credits"

- Potential future policy measures to promote zero-emissions for privately-operated ports

Source: FCH2 JU, Roland Berger, Shell

C.5 Aircraft

Auxiliary Power Units can further add to airport emissions and noise reductions while being more fuel efficient than traditional engines

Fuel Cell Powered Aircrafts

Background

> The aviation industry is currently shifting towards the concept of **'more-electric aircrafts'**, meaning electric power should be used for non-propulsive systems

> Here, **on-board auxiliary power units (APUs)** are mostly used during ground as well as on-flight times. Traditionally, they use jet fuel and consist of a gas turbine combined with an electrical generator

Technical characteristics

> **Fuel cell APUs** are an attractive alternative since they display **higher efficiencies** than jet-fuelled engines

> Hypothetical fuel cells designed for aircrafts of around 140 – 180 passengers typically have a designed capacity of 300 – 600 kW – real-life aircraft energy demand might be much higher, depending on the type and electrification level of the aircraft

Environmental considerations

> Up to **10% of airport emissions can be traced to APU systems** – hence, significant reductions of CO_2 emissions, pollutants and fine dust particles can be realized

Economic considerations

> No **TCO information disclosed** so far since fuel cell APUs are not pre-commercialised yet – demonstration projects are ongoing but fuel cell weight poses a major challenge

Source: Eurocontrol, American Institute of Aeronautics and Astronautics, FCH2 JU, Roland Berger

C.6 Airport ground handling equipment

Airport services are a complex ecosystem with multiple types of equipment – Potential for FCH applications in transport and energy

Snapshot of airport ground service ecosystem and FCH opportunities (selection)

	Description	Selected independent players
1 Ground handling	> **Ramp handling:** aircraft loading & unloading, marshaling, pushback, towing and repositioning, aircraft cleaning, toilet/water, … > **Passenger handling:** passenger check-in, ticketing, boarding, security and pre-board screening, … > **Cargo handling**	swissport WFS Worldwide Flight Services Menzies Aviation ASIG BBA Aviation dnata AVIAPARTNER
2 Catering	> **Food design and production** > **Food handling:** supply logistics, loading, backflow management, … > **Inventory management:** food, tableware, …	LSG Sky Chefs gategroup SERVAIR sats DO & CO dnata newrest
3 Others	> **Other handling services:** de-icing, fuelling, … > **Other passenger services:** lounge management, limo services, … > **Facility management:** e.g. distributed energy supply – stationary applications…	WFS Worldwide Flight Services Skytanking

XXX = Potential for FC applications

Source: FCH2 JU, Roland Berger

Towing tractors are one of the most advanced airport ground handling equipment with fuel cell technology so far

Use case and application characteristics

INDICATIVE

Description

> Fuel cell powered airport ground handling equipment 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 characteristics

> **Technical characteristics vary greatly** according to type, size and function of the specific equipment

> **Smaller vehicles** like luggage trucks, ACU, baggage loaders, water trucks and small fuel tank trucks **with energy requirements of less than 20 kW are most suitable** for FC applications in the medium-term

> FC towing tractors are currently one of the furthest developed FC ground handling equipment (towing capacity ~1,700 -2,200 kg, driving speed ~20-27 km/h) and require a ~17-22 kW engine, they need to be refuelled for 3 to 4 min once per working shift

Competing technologies

> Diesel, Battery-Electric, Diesel-battery hybrid, CNG/LPG

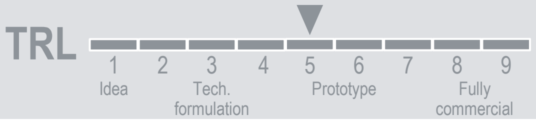
Sources: Industry publications, Mulag, Eurocontrol, FCH2 JU, Roland Berger

Airports have high security standards and are very cost-sensitive – the implementation of demonstration projects is a major challenge

Business case and performance overview – INDICATIVE

Technical/operational

- **Prototypes have been developed** for selected ground handling equipment
- Demonstration projects in operational environment are either completed or ongoing (albeit mostly outside Europe)
- **FC ground handling equipment is not commercialized yet**, successful demonstration projects in Europe need to be accelerated first
- **Challenges**: high airport security standards possibly impede the initiation of demonstration projects and the successful granting of regulatory permits, esp. for refuelling infrastructure



Economic

- **FC ground handling equipment demonstrates high system efficiency** and is low in maintenance- and operating costs
- **High CAPEX costs** are a big challenge to the cost-sensitive aviation industry
- **Key business case drivers**:
  - Cost of hydrogen vs. cost of diesel or electricity (in case of BEV competition)
  - System CAPEX
  - Infrastructure costs (esp. considering potential permitting challenges of implementing hydrogen refuelling and storage infrastructure in airports)

Environmental

- **Zero tailpipe (i.e. tank-to-wheel) emissions** of CO_2, pollutants such as NO_X and fine dust particles as well as significant noise reduction for FCH airport ground handling equipment – key benefit for workers and passengers as well as outside environment
- Well-to-wheel CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-wheel emissions for FCH airport ground handling equipment with "green hydrogen"**

Source: FCH2 JU, Roland Berger

Hence, governmental authorities need to path the way by supporting permits for hydrogen applications

Key considerations concerning fuel cell airport ground handling equipment

> **Authorities place increasing importance on decarbonisation and emissions reduction** and hence stimulate the development of zero-emission engines for airport ground handling equipment; additionally, **supranational regulations** from EU-level will require CO_2 monitoring and 'cap and trade' policies might be introduced in a second step

> **Necessary size/power ranges, capital cost and fuel supply** are among the major **hurdles** faced by airport operators wanting to adopt fuel cell ground handling equipment

> When **calculating total cost of ownership** for airport ground handling equipment, the **entire ecosystem should be taken into consideration** since hydrogen refuelling stations can be shared among multiple application cases

> Further **demonstration projects in Europe** will be necessary to **increase technological readiness and hence commercial availability** – governmental support will be necessary to bring technological changes to the highly regulated and security-focused industry

Source: FCH2 JU, Roland Berger

D. WG4: "Stationary applications"

D

Stationary applications find a broad audience amongst the regions and a dedicated industry coalition

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, CeresPower, VIESSMANN, eps, SOLID POWER, sunfire, PM PROTON MOTOR, ITM POWER, HyET Hydrogen, HYDROGENICS, Logan Energy, storengy

Each analysis consist of 3 key elements (use case, technologies, performance) – Regional differences will be tackled in Phase 2

Prel. business case components and flow of analysis – SCHEMATIC

Exogenous assumptions, e.g. energy/fuel cost, carbon intensities

FCH application

> Technical features (e.g. output, efficiency, lifetime, fuelling requirements) and general readiness

> Est. CAPEX / system cost

> Est. OPEX (e.g. maintenance)

… plus benchmarking against competing technologies

1 "generic" use case

…consisting of typical deployment requirements of European regions and cities

Basic performance

Technical / operational

Economic

Environmental

Source: FCH2 JU, Roland Berger

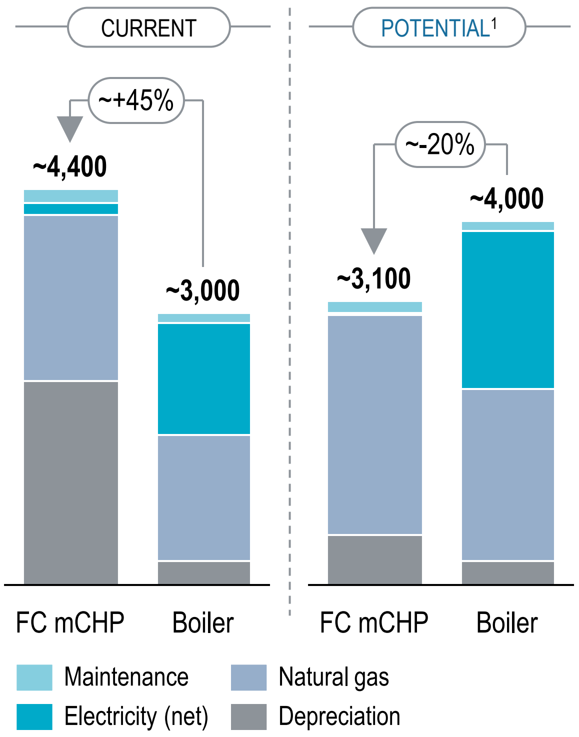
D.1 Residential mCHP

FC mCHP saves CO_2 but is hardly competitive with current standard solutions without subsidies – Future economics look promising

Business case and performance overview in two scenarios – INDICATIVE EXAMPLE

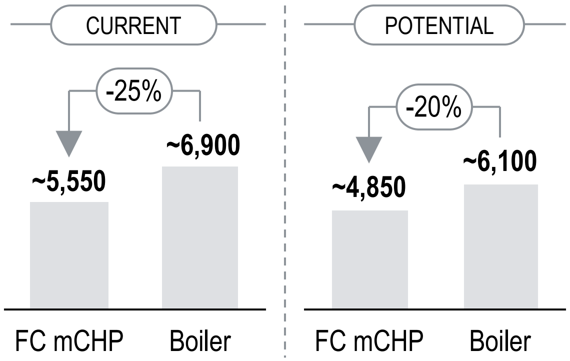
Economic

Total Cost of Energy (TCE) to household [EUR/year, annualized over 15 years]:



Environmental

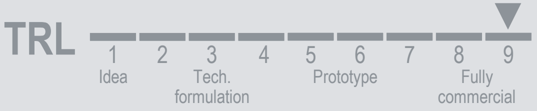
- > Next to zero local emissions of pollutants NO_x, SO_x and fine dust particles – here, e.g. potential elimination of NO_x
- > Total attributable CO_2 emissions dep. on CO_2 intensity of electricity mix and gas grid and "accounting method" – [kg CO_2 p.a.]:



- > Broader analyses across the EU put the estimated immediate CO_2-savings over grid+boiler between 20% and 85% dep. on specific use case, electricity mix and FC mCHP deployed

Technical/operational

- > One of the most mature FCH technologies overall: large scale field tests completed across Europe; adv. generation systems from various OEMs now commercially available, others have announced to follow in the near term (EU catching up to East-Asian markets)
- > Ready for large scale deployment as FC mCHP builds on existing natural gas infrastructure
- > For FC mCHP, system and fuel cell stack lifetime currently below conventional heating systems, expected to be met as systems progress along learning curve
- > Typically more physical space required in home than for simple condensing boiler, ideally separate room for heating equipment



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1) One exemplary long-term scenario (of many possible scenarios) with a set of changes in key variables (performance, cost, energy prices) – please see following slides

Source: FCH2 JU, Roland Berger

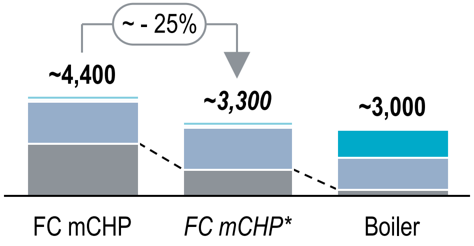
Capital cost, spark spread, efficiency and use case characteristics are the key business case determinants

Key performance determinants and selected sensitivities[1] – INDICATIVE EXAMPLES

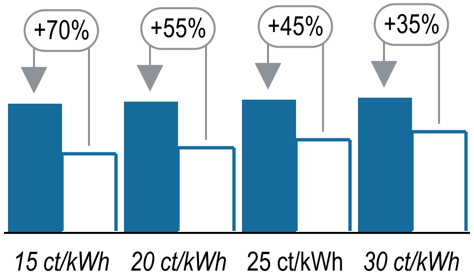
1. **Cost of FC mCHP:** significant potential for cost reductions and hence reduced purchase price (in current scenario, cutting CAPEX in half would lead to ~25% lower TCE in this use case) – key drivers are volume uptake / growing cumulative production per manufacturer
2. **Energy price levels / "spark spread":** high electricity prices and comparatively low gas prices support business case, especially when maximising in-house power consumption **– strong regional differences!**
3. **Electrical efficiency:** potential increases in electrical efficiencies (expected to grow to up 42% in next generation FC mCHPs) increase electricity production during FC mCHP operations and hence might reduce heating costs (see potential case)
4. **Use case characteristics and mCHP operations:** longer operating hours (e.g. in heat-intensive use cases tend to improve the FC's business cases due to higher electricity production **– strong regional differences!**
5. **Decarbonisation of electricity and gas grid:** significant savings in CO_2 and primary energy with FC mCHP, especially over the medium term and when grid electricity supply is dominated by conventional power generation; long-term greening of gas grid (via green hydrogen, biogas, etc.) helps sustain env. edge of distributed, gas-based generation over grid supply (with conv. gas or electr. heating) **– strong regional differences!**

Estimated TCE impact
[EUR/year]

Re. #1 Cutting CAPEX in half ...



Re. #2 Diff. electricity prices ...



🟦 Maintenance 🟦 Electricity (net) 🟦 Natural gas ⬛ Depreciation 🟦 FC mCHP ☐ Boiler + grid

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1) Unless otherwise stated, all statements shall be considered *ceteris paribus*, i.e. "all-other-things-equal"

Source: FCH2 JU, Roland Berger

We consider a representative residential use case, established technology assumptions and selected EU energy mix and prices

Preliminary business case components and key assumptions – INDICATIVE EXAMPLE

Application-related assumptions

current/*potential*	**FC micro-CHP**	**Gas Boiler** (+ Grid)
Technical specifications	Fully-integrated 1 kW$_{el}$ / 1.5 kW$_{th}$ fuel cell mCHP heating system incl. 20 kW$_{th}$ auxiliary condensing boiler, combined heat storage	State-of-the-art 20 kW$_{th}$ gas condensing boiler, connection to central electricity grid
CAPEX[1]	EUR 16,600 / *8,000*	EUR 4,000
Heating fuel	Natural gas	Natural gas
Ø net efficiency	37%$_{el}$, 52%$_{th}$ / *42%$_{el}$, 53%$_{th}$*	90%$_{th}$
Lifetime	10 / *15* years with 2 / *0* fuel cell stack replacements	15 years
Maintenance	EUR 140 / *120* p.a.	EUR 110 p.a.
Other aspects	Heat-driven operations of the FC mCHP acc. to standard load profiles, feed-in of any electricity not consumed in-house, some (peak) electricity demand covered by grid	All thermal energy from gas condensing boiler, all electrical energy from electricity grid

Use case and exogenous factors

Strongly dependent on reg. circumstances

- Partially renovated residential house in continental Europe with ca. 110 m^2 heated space, 5-person family, central heating system, connection to local gas and electricity grid
- Annual heat demand (incl. hot water): ~21,000 kWh
- Annual electricity consumption: ~5,000 kWh
- Resulting annual operations of the fuel cell mCHP in this use case:
  - ~6,000 full load hours
  - ~45% of thermal energy covered by FC mCHP, ~55% by aux. boiler
  - ~6,000 / *~7,100* kWh$_{el}$ produced (~65% / *~60%* consumed in-house)

Strongly dependent on reg. circumstances

- Cost of natural gas to household: 0.06 / *0.09* EUR/kWh
- Cost of grid electricity to household: 0.25 / *0.35* EUR/kWh
- CO_2 intensity of natural gas: 185 / *165* g/kWh
- CO_2 intensity of grid electricity: 510 / *350* g/kWh
- CO_2 balancing method for mCHP: power feed-in credits at average CO_2 intensity of power grid
- No public support schemes considered (subsidies, tax credits, feed-in tariffs, CHP premiums, etc.)

---

[1] Incl. installation and stack replacements as re-investments (e.g. short-term cost to be assumed at cost levels of 500 units per manufacturer, i.e. already significantly lower cost levels than actual current prices: system cost of EUR 11,000; installation cost EUR 1,600; stack replacement cost of 4,000)

Source: FCH2 JU, Eurostat, European Commission, Roland Berger

Please note the following:

> *Today's analysis showed an exemplary case of a fully-integrated fuel cell mCHP application with a heat-driven operating model. Several* ***other mCHPs with a baseload power model*** *exist as well; their business case (as well as market approach) has some important similarities and differences. We will briefly revisit their business case again for the sake of completion*

Source: FCH2 JU, Roland Berger

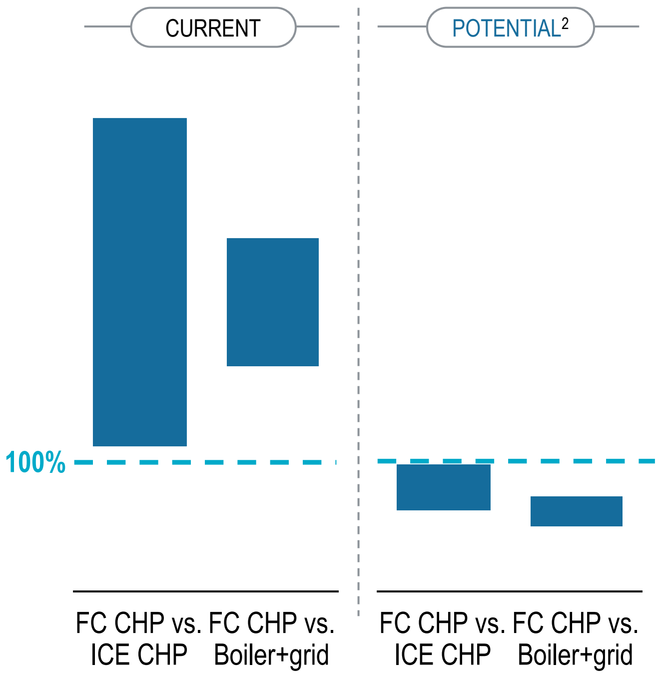
D.2 Commercial buildings

With growing volumes over the long term, FC CHPs can become competitive – Significant CO_2 and pollutant savings possible

Business case and performance overview[1]– INDICATIVE

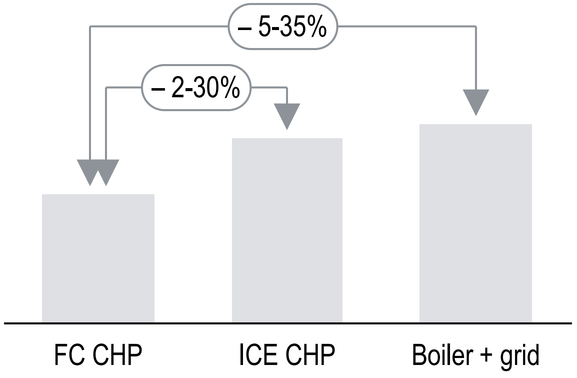
Economic

Multiples of FC CHP Total Cost of Energy (TCE) in different use cases (TCE of counterfactual at 100%):



Environmental

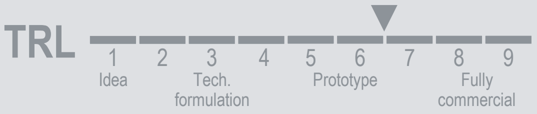
- Next to zero local emissions of pollutants NO_x, SO_x and fine dust particles
- Total attributable CO_2 emissions dep. on CO_2 intensity of electricity mix and gas grid and "accounting method" – CO_2 savings across different apartment use cases:



- Outlook: over the long term, the emissions performance will depend on the decarbonisation of the electricity and gas grids as well as increases in efficiency of FC CHPs

Technical/operational

- Limited range of products available in Europe that are mostly in advanced-prototype / demo-project stage (North American and East Asian markets are more mature), EU manufacturers starting to develop more products (prototype / demo or early commercial trial stage) **– initial focus on further demo projects**
- Ready for deployment as FC CHP would **build on existing natural gas infrastructure**
- For FC CHP, system and fuel cell stack lifetime currently below conventional heating systems, expected to catch up as systems progress along learning curve
- FC CHPs could e.g. be enabled by (in-house) power and heat contracting models to enable building owners & developers to shoulder (and finance) initial CAPEX



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1) Based on 8 use cases across 4 EU markets (DE, IT, PL, UK) as of 2015; ICE = gas-fuelled Internal Combustion Engine

2) Requiring significant volume increases, here e.g. 5,000 cum. units per manufacturer (ideally supported by synergies from other stationary FC segments)

Source: FCH2 JU, Roland Berger

Strong business case, high spark spread, high efficiency and greener natural gas will help FC CHPs succeed in the market

Key performance determinants and success factors

Business case awareness – from CAPEX and TCO/TCE perspective

In commercial use cases, economics tend to play a larger role in the decision making process – (1) creating the potential to sell on a TCO/TCE-based value proposition (i.e. significantly lower OPEX offsetting higher CAPEX) and (2) triggering the need to reduce cost sufficiently as customers will be hesitant to pay a significant premium

Electrical efficiency

Potential increases in electrical efficiencies boost electricity production during CHP operations and hence reduce TCE (expected to grow to up 58% in future generation FC CHPs, i.e. significantly more than ICE CHP at ca. 28-38% or micro gas-turbines at ca. 28%)

STRONG REGIONAL DIFFERENCES

Business model for market penetration

FC deployment in the complex stakeholder landscape (incl. e.g. owners/developers, facility managers, residents/tenants, planners, installers, utilities, etc.) might be overcome by contracting models where building owners (e.g. housing associations) plan, finance and deploy a new system and sell electricity and heat to residents

Energy price levels / "spark spread"

High electricity prices and comparatively low gas prices support business case (grid parity betw. 10-20 ct/kWh_{el} especially when maximizing in-house power consumption)

Decarbonisation of electricity and gas grid

Significant savings in CO_2 and primary energy with FC mCHP, especially over the medium term and when grid electricity supply is dominated by conventional power generation; long-term greening of gas grid (via green hydrogen, biogas, etc.) helps sustain env. edge of distributed, gas-based generation over grid supply (with conv. gas or electr. heating)

Source: FCH2 JU, Roland Berger

We primarily look at apartment buildings (or sets of family homes) that would use FC CHPs instead of gas boilers (or ICE CHPs)

Preliminary business case components and key assumptions – INDICATIVE

Application-related specification (selection)

current/*potential*	**Fuel Cell CHP (FC CHP)**	**Gas Boiler** (+ Grid)
Technical specifications	Combined ca. 5 kW$_{el}$ / ca. 4 kW$_{th}$ nat. gas FC CHP system in add. to <50 kW$_{th}$ condens. boiler and grid power supply, larger combined heat storage	State-of-the-art <50 kW$_{th}$ gas condens. boiler, grid power supply, comb. heat storage
CAPEX[1]	ca. 15,500 */ 11,000* EUR/kW$_{el}$	EUR 5-7,000
Heating fuel	Natural gas	Natural gas
Ø net efficiency	52%$_{el}$, 37%$_{th}$ */ 58%$_{el}$, 38%$_{th}$*	90%$_{th}$
Lifetime	10 */ 15* years with 1 */ 0* fuel cell stack replacements	15 years
Maintenance	EUR 650-850 */ 500-600* p.a.	EUR 110 p.a.
Other aspects	Heat-driven operations of the FC CHP acc. to standard load profiles, feed-in of any electricity not consumed in-house, some (peak) electricity demand covered by grid	All thermal energy from gas condensing boiler, all electrical energy from electricity grid

Use case and exogenous factors

Strongly dependent on reg. circumstances

> Apartment buildings (or set of family homes) (5-10 units, 20-30 residents) with 800-1,200 m^2 in building stock (possibly renovated) with single-source/central heating and DHW system

> Annual heat demand (incl. hot water): ~75,000-220,000 kWh – strongly dep. on size, degree of insulation, climate zone, etc.

> Annual electricity consumption: typically 900-1,500 kWh per resident

> Resulting annual operations of the fuel cell CHP in such use cases: 5,000-6,00 full load hours; dep. on load profile, ca. half of thermal energy covered by FC mCHP and majority of power demand supplied by FC CHP

> Cost of natural gas: equal or less than 0.04 */ 0.07* EUR/kWh

> Cost of grid electricity: equal or less than 0.20 */ 0.30* EUR/kWh

> CO$_2$ intensity of natural gas: 185 / 165 g/kWh

> CO$_2$ intensity of grid electricity: 510 */ 350* g/kWh

> CO$_2$ balancing method for CHP: power feed-in credits at average CO$_2$ intensity of power grid

> No public support schemes considered (subsidies, tax credits, feed-in tariffs, CHP premiums, etc.)

Strongly dependent on reg. circumstances

---

1) Incl. installation and stack replacements as re-investments (e.g. short-term cost to be assumed at cost levels of 100 units per manufacturer, i.e. already significantly lower cost levels than actual current prices: system cost of 10,900 EUR/kW; installation cost 1,600 EUR/kW; stack replacement cost of 3,000)

Source: FCH2 JU, Eurostat, European Commission, Roland Berger

The larger the FC (i.e. >20 or even >50 kW$_{el}$), the more crucial the efficient use of heat and the robustness of the overall business case

Key considerations with regard to FC CHPs for commercial use cases >20 / >50 kW$_{el}$

Changing business models

More and different stakeholders involved, less off-the-shelf and more made-to-order systems that are tailored to individual use case (key role of engineers/planners and installers); different opportunities for business model innovation (e.g. contracting, Energy Service Companies (ESCOs))

Need for sufficient on-site heat consumption

To reap the benefits of CHP (i.e. allowing for long operating hours and efficient self-consumption) need for constant heat demand on-site that is supplied by FC CHP – e.g. in buildings such as hospitals, hotels, swimming pools

Tougher competition from grid electricity supply

Generally speaking, lower grid electricity prices for higher-volume off-takers (like operators of the aforementioned buildings) – hence pressure on distributed CHP to achieve parity (>10 ct/kWh)

Opportunities for regions and cities

Procuring FC CHP as low-emission, innovative systems for public buildings thereby broadening the European base of key demonstration projects and supporting initial volume uptake

Source: FCH2 JU, Roland Berger

D.3 Industrial use cases

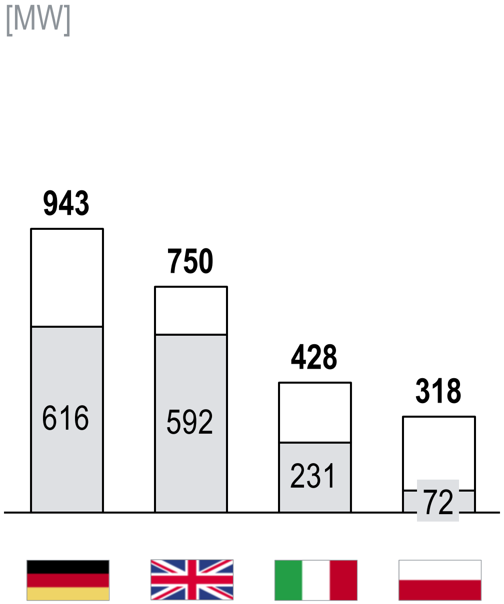
In industrial use cases, fuel cells can tap into the annual market for gas-fired on-site generation – several GW in core EU markets

Annually addressable market in four focus countries

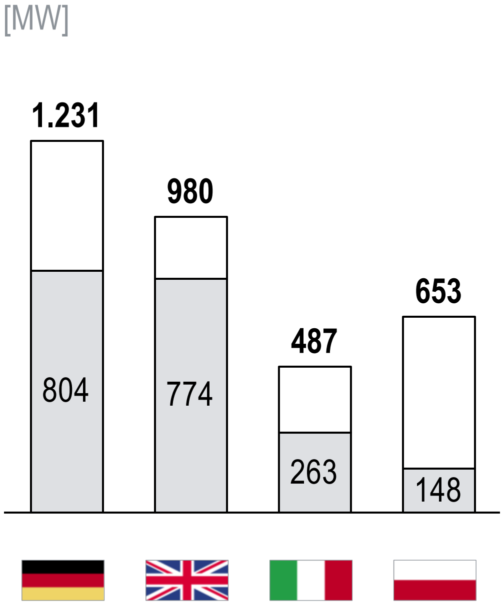
Industrial

- **Fuel cell CHPs and prime power** in power ranges from ca. 400 kW_{el} and into the multi-MW range for industrial applications
- **Primary markets** include gas-fired distributed generation
- **Conversion markets** comprise non-gas distributed generation
- Forecast based on expected market growth

2012 addressable market



2030 addressable market



☐ Conversion markets [installable capacity] ▨ Primary markets [installable capacity]

Source: IHS; National statistics institutes; Oxford Economics; FCH2 JU, Roland Berger

We consider three exemplary use cases for large-scale stationary fuel cells in MW-range: combined heat and power and power-only

Examples for industrial use cases (selection) – INDICATIVE

Use cases

- **Data center** with annual power demand of 8,000 MWh (fluctuation of 70-100%) and prime power technology installed, cooling is a major power consumption driver
- Max. necessary power load at ca. 1,000 kW_{el} with typically grid supply and closed, auxiliary power system, based on natural gas
- Connection to natural gas and electricity grid
- Technologies: Grid, FC (power-only or "prime power") with ca. 1.0 MW_{el}

- **Pharmaceutical production facility** with annual base load demand of ca. 11,600 MWh and equivalent heat demand, optimally served by a CHP system
- Max heat load ca. 1,100 kW_{th} and power load at ca. 1,400 kW_{el}
- Typically no relevant power fluctuation with natural gas as main fuel
- Connection to natural gas and electricity grid
- Technologies: Grid + boiler, ICE CHP, microturbine CHP, FC CHP with ca. 1.4 MW_{el}

- **Chemical production facility** with high thermal power demand of ca. 29,000 MWh p.a. and electric demand of ca. 12,000 MWh for industrial processes
- Assumed CHP technology with max. heat load of ca. 1,100 kW_{th} and power load at 1,400 kW_{el} based on natural gas
- Connection to natural gas and electricity grid, potential for on-site biogas supply
- Technologies: Grid + boiler, ICE CHP, microturbine CHP, FC CHP with ca. 1.4 MW_{el}

Typical exogenous assumptions

- **Cost of natural gas**: e.g. betw. 0.020 and 0.040 EUR/kWh
- **Cost of grid electricity**: e.g. betw. 0.055 and 0.145 EUR/kWh (key markets with highest industrial electricity markets are e.g. UK and Italy)
- **CO_2 intensity of natural gas**: 185 g/kWh (potentially decreasing)
- **CO_2 intensity of grid electricity**: e.g. on average ~500-550 g/kWh in many parts of continental Europe with high shares of coal-fired power generation, ~350 g/kWh in the UK (all gradually decreasing over the coming years)
- **CO_2 balancing method for CHP**: power feed-in credits at average CO_2 intensity of power grid
- **No public support schemes considered** (subsidies, tax credits, feed-in tariffs, CHP premiums, etc.)

Source: FCH2 JU, Eurostat, European Commission, Roland Berger

Large-scale fuel cells face three main natural gas competitors – large boilers, CHP engines and CHP micro-turbines

Comparison of benchmark applications – INDICATIVE

current / potential	**Fuel Cell CHP** (FC CHP)	**FC Prime Power** (FC PP)	**Electricity grid + gas cond. boiler**	**Gas ICE CHP**	**Gas turbine CHP**
Technical specifications	Combined ca. 1.4 MW$_{el}$ / ca. 1.1 MW$_{th}$ nat. gas FC CHP system (SOFC, MCFC)	1.0 MW$_{el}$, typically low-temp. polymer electrolyte FC (PEM FC) or solid oxide FCs (SOFC)	State-of-the-art 1.5 MW$_{th}$ gas condens. boiler	State-of-the-art 1.5 MW$_{el}$ comb. engine	State-of-the-art 1.4 MW$_{el}$
CAPEX[1)]	EUR/kW$_{el}$ ca. 3,200 – 3,400 / *2,900 – 3,100*	EUR/kW$_{el}$ ca. 5,100 – 5,300 / 3,500 - 3,700	EUR/kW$_{th}$ ca. 70-80	EUR/kW$_{el}$ ca. 1,200-1,300	EUR/kW$_{el}$ ca. 1,600-1,700
Heating fuel	Natural gas / biogas	Natural gas / biogas	Natural gas / biogas	Natural gas / biogas	Natural gas / biogas
Efficiency	49%$_{el}$, 31%$_{th}$ / *61%$_{el}$, 31%$_{th}$*	49%$_{el}$ / *61%$_{el}$*	95%$_{th}$	40%$_{el}$, 48%$_{th}$	28%$_{el}$, 50%$_{th}$
Lifetime	16 / *17* years with 3 / *3* fuel cell stack replacements	11 / 14 years with 3 / 3 FC stack replacements	Ca. 15 years	Ca. 15 years	Ca. 15 years
Maintenance	EUR/kW$_{el}$ ca. 50 - 60 / *45 -55* p.a.	EUR/kW$_{el}$ ca. 45 - 55 / 45 -55 p.a.	EUR/kW$_{th}$ ca. 10-15 p.a.	EUR/kW$_{el}$ ca. 90-110	EUR/kW$_{el}$ ca. 65-75 p.a.
Other aspects	Power-driven system with base-load focus and >130°C temp. required for heat	Typically base-load and load-following operation with adaptable power output (through modulation)	n/a	n/a	n/a

1) Incl. installation and stack replacements as re-investments (e.g. Fuel Cell CHP short-term cost to be assumed at cost levels of 100 units per manufacturer, i.e. already significantly lower cost levels than actual current prices: system cost of 2,300 EUR/kW; installation cost 400 EUR/kW; stack replacement cost of 590 EUR/kW)

Source: FCH2 JU, Roland Berger

With growing production volumes over the long term, large scale FC CHPs can become competitive – much depends on the use case

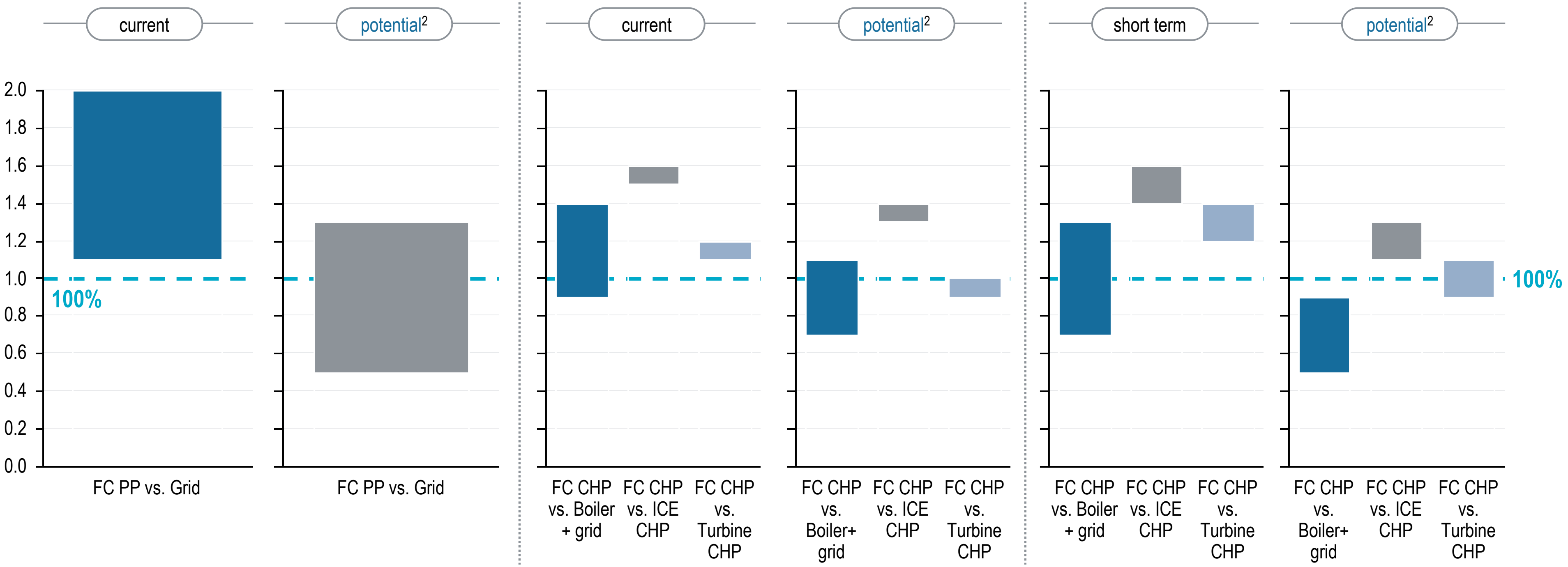
Business case and performance overview[1]– INDICATIVE

Data centre

Pharmaceutical production facility

Chemical production facility

Multiples of FC CHP Total Cost of Energy (TCE) in different use cases (TCE of counterfactual at 100%) with highest and lowest multiples as boundaries – i.e. a TCE multiplier <1 (or <100%) indicates lower TCE of the fuel cell technology compared to the counterfactual



1) Based on 3 use cases across 4 EU markets (DE, IT, PL, UK) as of 2015; ICE = gas-fuelled Internal Combustion Engine

2) Requiring significant volume increases, here up to 50 MW installed capacity per manufacturer

Source: FCH2 JU, Roland Berger

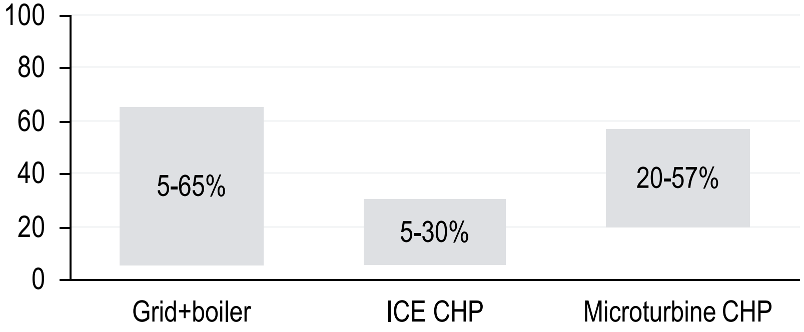
CO_2 savings well above 50% are possible thanks to highly efficient distributed generation, NO_x can be reduced significantly as well

Business case and performance overview[1]– INDICATIVE

Environmental

> **Drastic reduction of local emissions of pollutants NO_x, SO_x, fine dust particles** – potentially significant benefit in urban areas, < 1 mg/Nm³ for FC vs. < 250 mg/Nm³ for lean-burn gas ICE (without external NO_x abatement technology)

> **Significant CO_2 savings**; total attributable CO_2 emissions dep. on CO_2 intensity of electricity mix and gas grid and "accounting method" – CO_2 savings across different industrial use cases [%]:



> **Outlook**: over the long term, the emissions performance will depend on the decarbonisation of the electricity and gas grids as well as increases in efficiency of FC CHPs

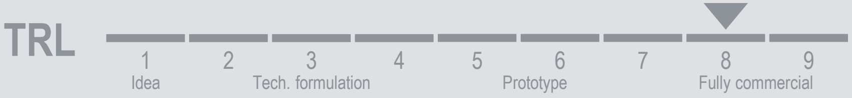
Technical/operational

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

> Ready for deployment as industrial FC CHPs would **build on existing natural gas infrastructure or use fuel-supply on site (e.g. biogas, hydrogen)**

> For FC CHP, **system lifetime are at par** with competing technologies such as ICE or micro-turbine CHPs

> For any onsite generation, industrial sector primarily concerned with ensuring that its core business is not disrupted – **FC needs to operate seamlessly** with existing infrastructure and cause min. disruption to ongoing productivity



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1) Based on 5 use cases across 4 EU markets (DE, IT, PL, UK) as of 2015; ICE = gas-fuelled Internal Combustion Engine

Source: FCH2 JU, Roland Berger

Strong business case (via lower CAPEX), higher efficiencies and innovative financing models (e.g. ESCo) are key success factors

Key performance determinants and success factors

Business case awareness – from CAPEX and TCO/TCE perspective

In industrial use cases, economics are virtually all that matter in the decision making process and decision makers look for payback periods (typically well below 5 years) – (1) creating the potential to sell on a TCO/TCE-based value proposition (i.e. significantly lower OPEX offsetting higher CAPEX) and (2) triggering the need to reduce cost (esp. CAPEX) sufficiently

Electrical efficiency

Potential increases in electrical efficiencies boost electricity production during CHP operations and hence reduce TCE (expected to grow to up 51% in future generation large scale FC CHPs, i.e. significantly more than large-scale ICE CHP at ca. 38-40% or micro gas-turbines at ca. 20-28%)

STRONG REGIONAL DIFFERENCES !

Business and financing models for market penetration

Industrial users are likely more open to alternative business models; CAPEX burdens can be more efficiently distributed. E.g., the ESCo ("Energy Service Company") model is a very relevant (esp. high electricity price) "beachhead" as the end-user is not exposed to any upfront capital cost (particularly advantageous against low payback thresholds). The ESCo model allows the end-user to save money right away – while all operational risks are with the ESCo

Competition from grid electricity supply

Grid parity is below 10 ct/kWh_{el} in many places around Europe; moreover, mature competing distributed generation technologies are available. Esp. CAPEX have to be considerably reduced. High electricity prices and comparatively low gas prices support business case thanks to high electrical efficiency

Source: Delta EE, FCH2 JU, FCH2 JU, Roland Berger

Use case selection, (NO_x) emission limits and policy support are key commercialisation levers for Regions and Cities

Key considerations for regions and cities

Use cases: exposure to high electricity prices, possibly with on-site fuel supply

To reap benefits of large scale, highly efficient on-site generation with large-scale fuel cells, exposure to high electricity grid prices is a key driver; moreover, need for constant heat demand on-site that is supplied by FC CHP – e.g. in heat-intensive industries; also, on-site availability of (low carbon) fuel – e.g. biogas as byproduct – can render individual use cases even more attractive

Emissions: stricter limits on pollutant emissions (esp. NO_x) as opportunity for fuel cells

In the future, NO_x emission limits are likely to become more stringent, possibly much more so (e.g. European Commission's Medium Combustion Plant Directive (MCPD)) with current proposal of max. 95 mg/Nm^3 (at 15% O_2) will be applied to all new gas engine installations. Resulting need for NO_x abatement, improves the economic case for fuel cells (by improving the marginal capital and operating costs) over gas engines

Policy support: various possibilities for effective support

Given "total business case" or "project economics" logic of many industrial developers for on-site generation, various policy instruments can positively affect the business case – e.g. CHP generation premiums, feed-in tariffs, tax credits, subsidies, soft loans, etc.

Source: Delta EE, FCH2 JU, FCH2 JU, Roland Berger

D.4 Back-up power

FC back-up power systems are an attractive alternative for areas affected by insufficient grid reliability

Use case and application characteristics

INDICATIVE

Description

- > Fuel cell powered back-up electricity systems **can improve the reliability, "resilience" and quality of power supply for critical infrastructure** (e.g. data centers, hospitals, public security facilities, telecommunication infrastructure) by **bridging power outages** and providing **gird-independence**
- > Depending on **local regulation, grid reliability the specific use case**, back-up power needs to be available for several hours or even a few days

Technical characteristics

- > Fuel cell **powered back-up systems for uninterrupted power supply** (UPS) typically use compressed hydrogen gas (or has a fuel to generate electricity via a fuel cell-based energy converter
- > They can **bridge power outages for up to ca. 95 hours** (depending on the size of the fuel cell and storage of hydrogen or fuel availability)

Competing technologies

- > Diesel generators, Batteries

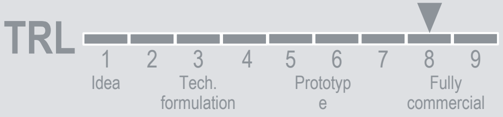
Sources: FCH2 JU, Roland Berger, Industry publications

High CAPEX costs can be counterbalanced by lower operating- and maintenance costs, but need to be reduced further

Business case and performance overview – INDICATIVE

Technical/operational

- Various **demonstration projects** have shown **technological maturity**
- Several variations and types of **FC back-up power** solutions are already **commercially available** and can be bought from multiple providers
- **Challenges:**
  - High **regulatory standards** for reliability of back-up power systems (e.g. for hospitals)
  - Structurally more robust power grids in Europe than in other industrialised or emerging markets, lower risk of (longer) power outages



Economic

- **FC back-up power systems demonstrate high system efficiency** and are low in maintenance- and operating costs (e.g. potentially less expensive total fuel cost, as diesel tanks typically have to be periodically refuelled irrespective of actual use)
- **High CAPEX costs** remain a big hurdle as rare but economic operational periods can't offset high upfront investment
- **Total expenditures on FC back-up power** systems are expected to be **lower** than total expenditures on battery/diesel back-ups in the medium- to long-run, under favourable conditions
- **Key business case drivers**:
  - System CAPEX
  - Cost of hydrogen vs. cost of diesel

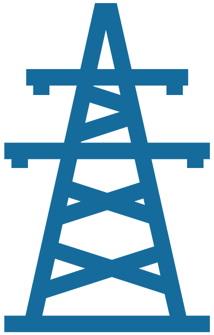
Environmental

- **Zero tailpipe (i.e. tank-to-power) emissions** of CO_2, pollutants such as NO_X and fine dust particles as well as significant noise reduction for FC back-up power solutions – key benefit for residents as well as outside environment
- Well-to-power CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-power emissions for FC back-up power systems with "green hydrogen"**

Source: FCH2 JU, Roland Berger

Nevertheless, a sufficient hydrogen supply infrastructure needs to be in place in order to accelerate deployment

Key considerations concerning fuel cell back-up power systems



- **Necessary system reliability, competitive TCO (incl. reasonable capital cost) and secure fuel supply** are among the most important assessment criteria for operators wanting to adopt fuel cell back-up power
- **Relatively lower OPEX potentially offset higher CAPEX for FC back-up power** in the medium to long run, depending on the specific deployment conditions and cost reductions of FC system
- **Sufficient hydrogen supply must be ensured** since **all back-up power systems located within the same area must be refilled at the same time** (after a power outage has occurred)
- **Governmental incentives** will be **necessary to shift the highly regulated back-up power industry standard** from diesel to fuel cells
- **Authorities place increasing importance on decarbonisation and emissions reduction** and hence stimulate the development of zero-emission back-up power solutions, also in order to avoid potential oil spills; additionally, **supranational regulations** from EU-level will require CO_2 monitoring and 'cap and trade' policies might be introduced in a second step

Source: FCH2 JU, Roland Berger

D.5 Off-grid power

Hydrogen fuel cells for off-grid solutions possess numerous advantages compared to conventional Diesel-powered generators

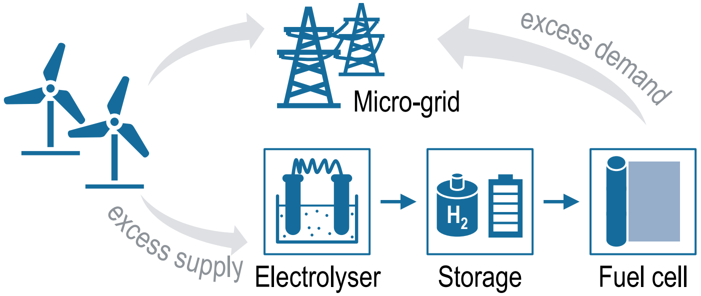
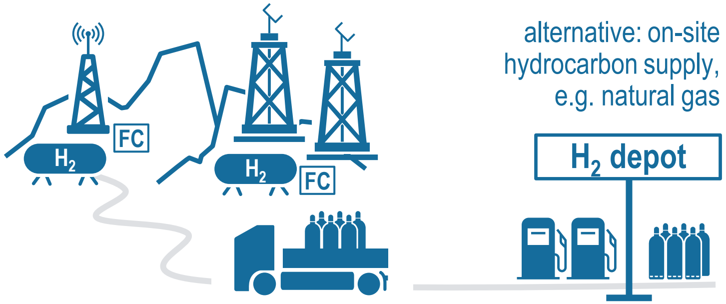
Benefits of FCH off-grid applications

- (Theoretical) possibility of full zero-carbon energy autarky in combination with renewable energy sources, electrolyser and storage system
- Higher operating efficiency (combustion and storage) and extended runtimes, compared to conventional technologies
- High reliability even under extreme climate conditions and seasonal variations
- Environmentally friendly (zero emissions, less regulatory problems or permitting hurdles in environmentally protected areas)
- Low maintenance frequency and thus low maintenance cost
- High flexibility and adaptability to power demand changes

Source: FCH2 JU, Roland Berger

Off-grid applications of stationary fuel cells can be segmented into two broader categories of use cases

Categories of use cases for off-grid fuel cell solutions – SCHEMATIC

	1. End-to-End FCH system	2. FC with external fuel supply
Layout		
Use cases (examples)	Stand-alone settlements in remote areas such as islands, mountain refuges, industrial sites, mining facilities, telco infrastructure, micro-grids/self-sufficient communities	Telco infrastructure (e.g antennas), television and radio repeaters, natural gas pipeline systems, remote residential areas
Alternatives	Renewable energy sources in combination with fossil-fuel generators and/or batteries	Fossil fuel generators (usually diesel, but also LPG, CNG, gasoline), possibly renewable energy sources in combination with batteries
Requirements/ Operating Model	Power range: several kW – up to multiple MW Fuel cells provide complementary power from green H_2 produced by electrolyser from renewable electricity	Power range: >1-2 kW Typically continuous supply of baseload power, fuelled e.g. with externally supplied H_2
Challenges	Demand and supply fluctuations (renewables), high setup cost, reliability of overall system	Dependency on fuel prices, accessibility / fuel supply routes, high setup cost, reliability of overall system

Source: FCH2 JU, Roland Berger

As off-grid solutions, stationary fuel cells typically face the conventional competitor of fossil fuel (Diesel) generators

Comparison of fuel cells and diesel generators (e.g. use case #2) – INDICATIVE

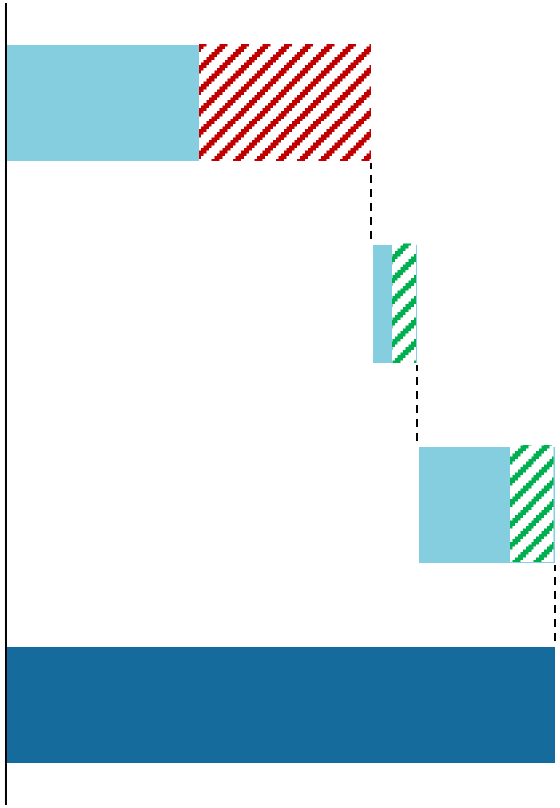
	Stationary fuel cell system (power-only or CHP)	**Diesel generator system** Reference model: CAT C4.4
Technical specifications	Combined ca. 50-100 kW$_{el}$ FC power-only or CHP potentially combined with other added systems like heat storages (if warranted by use case) 	72kW (prime) to 80kW (standby), 4-stroke Diesel engine, 230-480V, 50/60Hz @1,500/1,800 RPM 
CAPEX	Ca. 3,000-4,000 EUR/KW$_{el}$ (fuel cell module)	Ca. 800-1,000 EUR/kW$_{el}$
Fuel	Hydrogen, natural gas, LPG/CNG, biogas, etc.	Diesel fuel (tank capacity e.g. >200 litres)
Efficiency	50-60%$_{el}$, 30-40%$_{th}$	30%$_{el}$
Lifetime	Dep. on use case and target operating model	20-25 years
Maintenance	ca. 40 EUR/kW/a (or even lower)	ca. 40 EUR/kW/a
Other aspects	Several fuel cell technologies generally available (e.g. PEM, SOFC) – dep. on fuel availability, operating model, load profiles and other use case requirements	Mature technology available from a range of suppliers, engine can (in principles) be overloaded (e.g. to 110%)

Source: Shell, CAT, FCH2 JU, Roland Berger

TCO for both technologies have common drivers but heavily depend on the individual use cases – Fuel cells can compete in the long run

Schematic outline of technology-specific TCO for use case #2 – SIMPLIFIED

Total Cost of Ownership (TCO)
(e.g. in EUR per year / per kWh)



	Stationary fuel cell system	**Diesel generator system**
Capital cost	> Higher cost per kW installed > Higher development and permitting cost	> Lower cost per kW installed > Maturity level reached, low development cost
Op's & Maint.	> Less frequent maintenance routine > Lower overall maintenance cost	> Higher maintenance frequency, more need for spare parts > Higher overall maintenance cost
Fuel cost	> Higher efficiency, possibly more expensive fuel prices (external delivery), high delivery cost of H_2 > Likely lower overall fuel cost	> Lower efficiency, potentially lower fuel prices, high delivery cost > Likely higher overall fuel cost

Take-away Currently, the high capital costs make fuel cells the more expensive alternative. However, further performance improvements and cost reductions can lead to a better cost position than conventional fossil fuel generators in the future

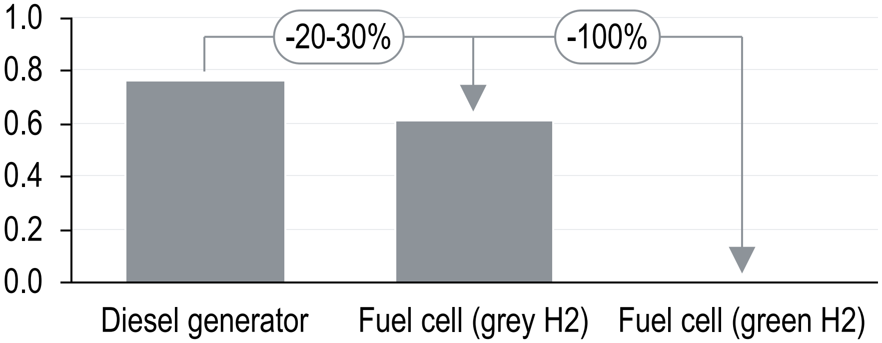
Source: FCH2 JU, Roland Berger, Shell ▨ Additional **cost** for fuel cell ▨ Additional **savings** through fuel cell

Large CO_2 savings are possible for FCs with low-carbon fuel; commercial readiness is relatively advanced

Business case and performance overview – INDICATIVE

Environmental

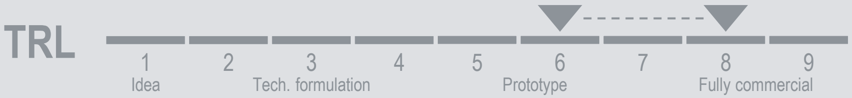
- > **Drastic reduction of local emissions of pollutants NO_x, SO_x, fine dust particles** – potentially significant benefit in remote areas that may be under conservation
- > **Significant CO_2 savings**; total attributable CO_2 emissions dep. on CO_2 intensity of supplied hydrogen (grey vs. green):



- > **Outlook**: over the long term, the emissions performance will depend on the share of green hydrogen used and the amount of CO_2 emitted by delivery logistics to the site

Technical/operational

- > **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**
- > Ready for deployment as fuel cells provide necessary **reliability for off-grid applications**, require infrequent maintenance and **fuel supply** can be assured in multiple conceivable scenarios
- > For FC CHP, **system lifetime** is **slightly below** lifetime of Diesel generators
- > Modular scalability ensures flexible adaptation according to demand



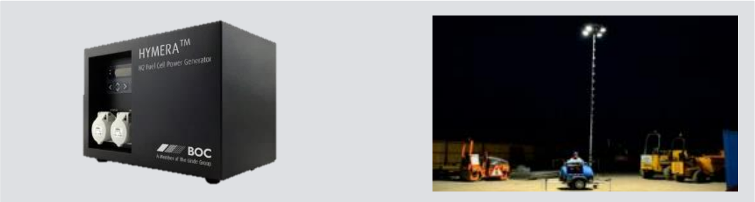
Source: FCH2 JU, Roland Berger

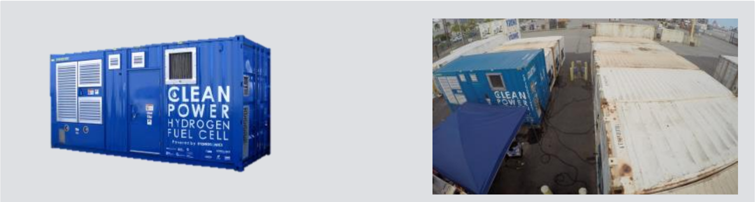
D.6 Gen-sets

Possible application cases for FC gen-sets vary greatly, especially with respect to their energy demand

Possible use cases for FC gen-sets[1]

EXEMPLARY AND INDICATIVE





	1 Construction sites	2 Refrigerated containers
Description	Construction sites need to ensure sufficient energy supply to satisfy **temporary energy demands like lighting**, especially during night and winter times in **remote areas** such as constructions at highways, rail tracks or in tunnels. In contrast to diesel generators, FC generators are a **quiet and environmentally friendly** alternative	Refrigerated containers need to be supplied with **energy during all transportation phases** – during storage times as well as while being transported. FC generators fitted in a redesigned container represent an efficient solution to supply them with energy, independent from local energy supply. **One FC generator can provide power for up to ~10-12 containers**
Characteristics		
- Output	~150-175 W peak power	>100 kW
- Capacity	~6-7 kWh (assuming 50% efficiency and a standard tank)	~10-12 h runtime on one tank fill (90 kg H_2)
- Price	EUR ~2,000 – 2,500	EUR ~ 700,000 – 800,000
Competing Technologies	Diesel	Diesel

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1) Additional use cases could for example include lighting towers, CCTV towers, environmental monitoring, offshore power and wildlife photography

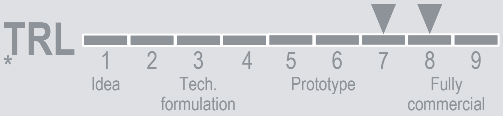
Source: FCH2 JU, Roland Berger, BOC, Fuel Cell & Hydrogen Energy Association, Sandia National Laboratories, Fuel Cell Today

Outside of Europe, fuel cell gen-sets are already commercialised – the European market should look to catch up

Business case and performance overview – INDICATIVE

Technical/operational

- > Fuel cell gen-set systems are **commercially available** in a variety of sizes, power ranges and application possibilities **outside of Europe**
- > However, in **Europe** the segment is still in the advanced **prototyping/ demonstration-project phase**
- > **Challenge:** hydrogen fuel supply and storage on-site – fit-for-purpose for transportable stationary fuel cells, e.g. hydrogen infrastructure must become available at container storage facilities



Economic

- > **Higher system efficiency**, lower maintenance and operating costs have the potential of counterbalancing relatively higher capital costs of FC gen-sets vs. conventional generators
- > **Key business case drivers**:
  - – Cost of hydrogen vs. cost of diesel
  - – Gen-set CAPEX vs. generator CAPEX
  - – Hydrogen supply and hydrogen infrastructure costs, esp. refuelling station CAPEX (incl. utilisation) and OPEX

Environmental

- > **Zero tailpipe (i.e. tank-to-power) emissions** of CO_2, pollutants such as NO_X and fine dust particles for FCH gen-sets as well as significant reduction of noise and vibrations – key benefits for workers as well as outside environment
- > **Lower noise emissions as key benefit for storage**, esp. if located close to urban areas
- > Well-to-power CO_2 emissions depend on fuel source, use case characteristics and efficiency (i.e. fuel consumption) – **potential for zero well-to-power emissions for FCH gen-sets with "green hydrogen"**

Source: FCH2 JU, Roland Berger

To accelerate FC gen-set deployment in Europe, the hydrogen infrastructure needs to improve significantly

Key considerations concerning FC gen-sets

A **Direct usability by Regions & Cities:** due to its diverse field of application, e.g. at municipal construction sites, FC gen-set deployment can be enhanced directly by Regions & Cities, especially as demonstrational projects in order to increase technological readiness and hence foster commercial availability in Europe

B **Hydrogen supply infrastructure:** An extensive hydrogen infrastructure needs to be developed by public authorities in order to facilitate FC gen-set deployment for companies, e.g. for construction sites, event locations

C **Capital costs:** High CAPEX costs are among the major concerns faced by operators interested in deploying FC-powered gen-sets

D **Environmental benefits:** Increasing emphasize on decarbonisation and emissions reduction is accelerating the deployment of zero-emission gen-sets, supranational cap and trade policies might further stimulate the attractivity of FC gen-sets for operators

Source: FCH2 JU, Roland Berger

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

WG 5 covers options of sourcing hydrogen and using it in the context of grid related optimization

Working Group 5: Energy-to-hydrogen applications

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 Advanced Hydrogen Solutions
SEMA consulting
HyET Hydrogen
BOC A Member of The Linde Group
H2B2
ITM POWER
SOLID POWER
uniper
CALVERA Hydrogen

Initially, we focus on the cost of hydrogen production, especially for green hydrogen – Monetisation covered by other Working Groups

Hydrogen value chain and business case mapping

Schematic/Simplified

Fuel supply 1

- Electricity
- Biogas
- Natural gas
- Other fuels

H_2 production 2

- Electrolysis / "green"[2]
  - Alkaline
  - PEM
  - (Solid-oxide)
- Biogas SMR / "clean"
- Steam-methane reforming (SMR)
- Other technologies

Initial focus of WG5

H_2 logistics[1] 3

- Transport, e.g. pipelines, trucking
- Distribution and retail, e.g. HRS
- Storage, e.g. central / decentral

Production cost in EUR/kg

End use[1] 4

- Hydrogen to mobility
- Hydrogen to industry
- Electricity and or heat generation from Hydrogen, e.g. P2P
- *Injection of hydrogen into the gas grid*
- Other

End user price in EUR/kg

Hydrogen production / cost perspective

Hydrogen monetisation / revenue perspective

---

[1] Covered in parts by Working Groups 1-4 (where part of the scope of work), esp. end user applications in transport and energy (stationary)

[2] Add. monetisation / revenue stream from electricity grid services – reducing the cost of hydrogen production

Source: FCH2 JU, Roland Berger

E.1 Green hydrogen production/power-to-hydrogen

Production cost of hydrogen critically depend *inter alia* on full load hours, installed capacity and effective power input cost

Approximation of cost of green H_2 – 2017 Scenario

Indicative/Simplified

@ 2,500 hrs FTE p.a.

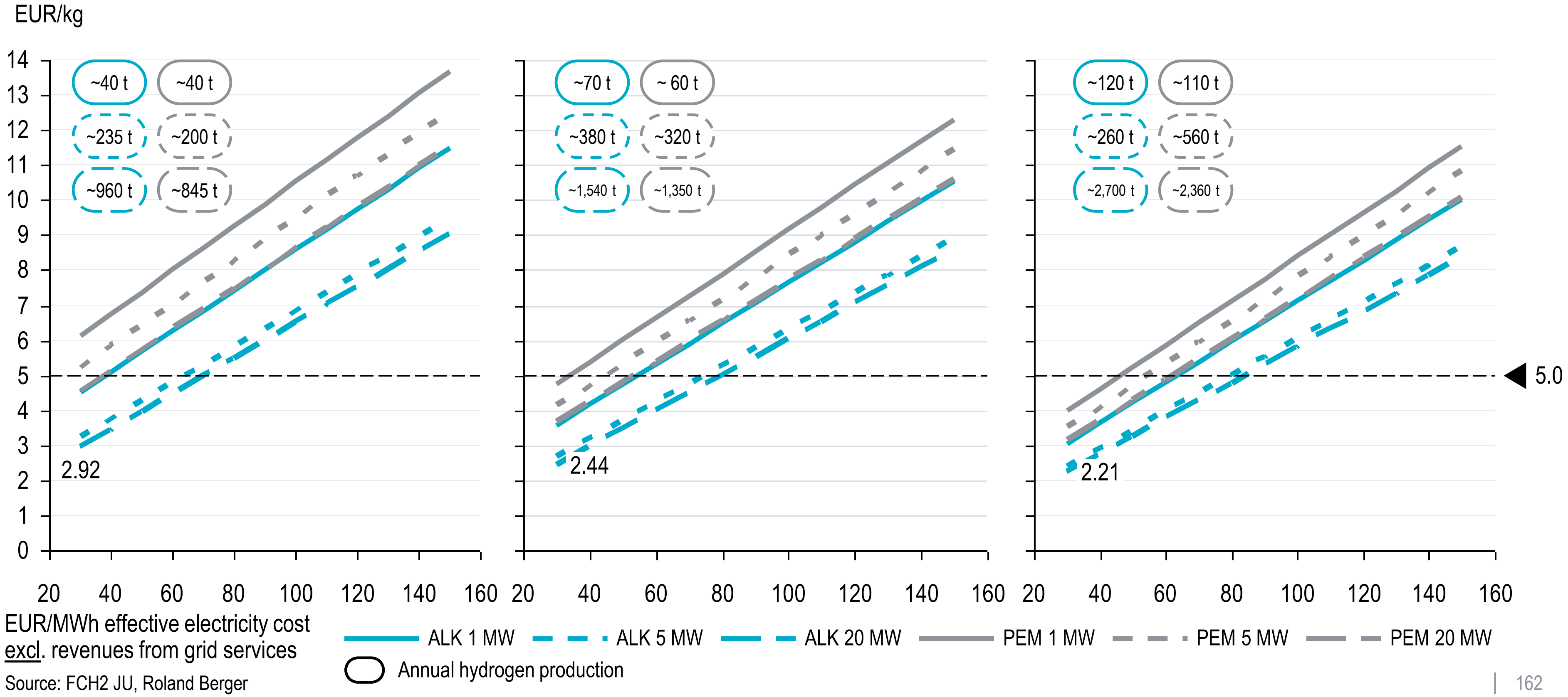
… e.g. onshore wind central EU

@ 4,000 hrs FTE p.a.

… offshore wind northern EU

@ 7,000 hrs FTE p.a.

… baseload hydropower central/northern EU



Source: FCH2 JU, Roland Berger

With lower cost and higher efficiencies, green hydrogen production cost are expected to decrease further in the long run

Approximation of cost of green H_2 – 2025 Scenario

Indicative/Simplified

@ 2,500 hrs FTE p.a.

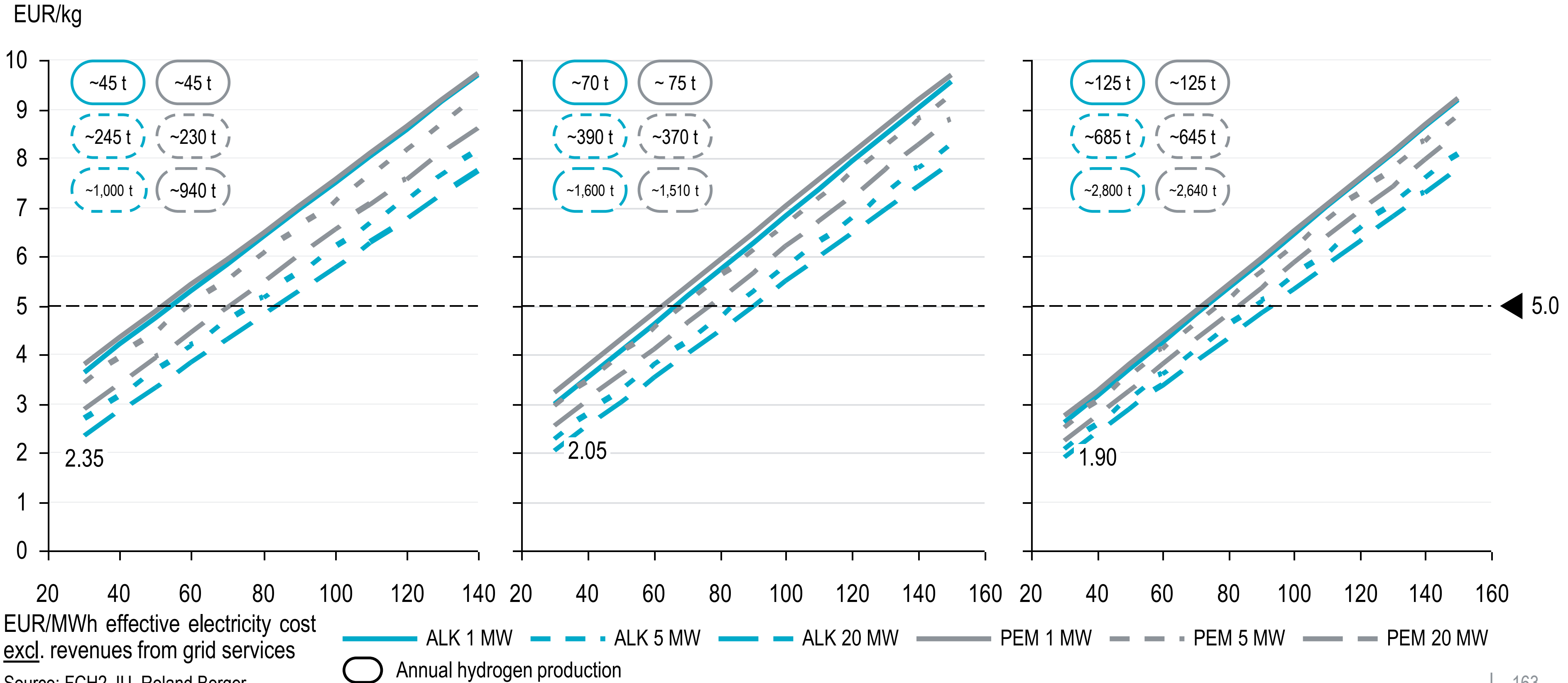
… e.g. onshore wind central EU

@ 4,000 hrs FTE p.a.

… offshore wind northern EU

@ 7,000 hrs FTE p.a.

… baseload hydropower central/northern EU



Source: FCH2 JU, Roland Berger

The cost of electricity is the largest cost component of the cost of green hydrogen production

Indicative cost break-down

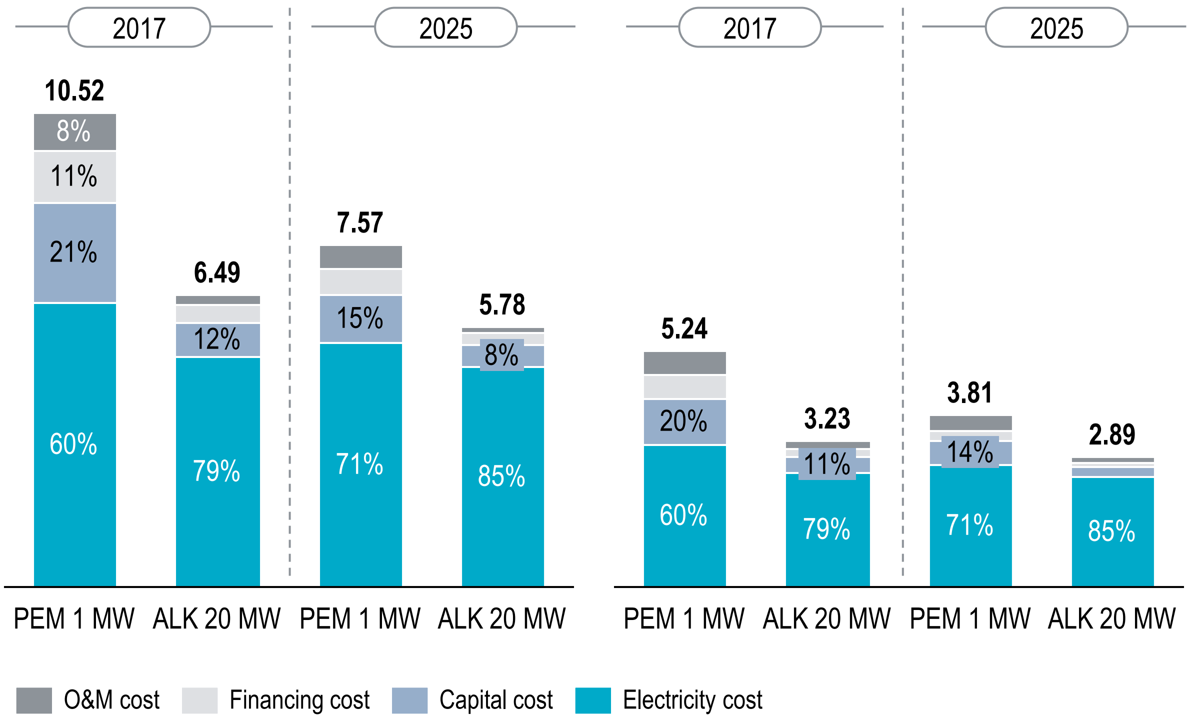
Indicative/Simplified

@ 2,500 hrs FTE p.a. [EUR/kg]

… @ 10 ct/kWh effective electricity cost

@ 7,000 hrs FTE p.a. [EUR/kg]

… @ 5 ct/kWh effective electricity cost



> Cost of electricity makes up the largest part of the cost of production, followed by capital cost

> Hence, the effective price of electricity is the key driver of any green hydrogen business case (on the cost side) – dep. on marginal cost of electricity, taxes, levies, surcharges, etc.

> Structural cost reductions come from lower CAPEX, higher efficiencies and longer stack lifetimes

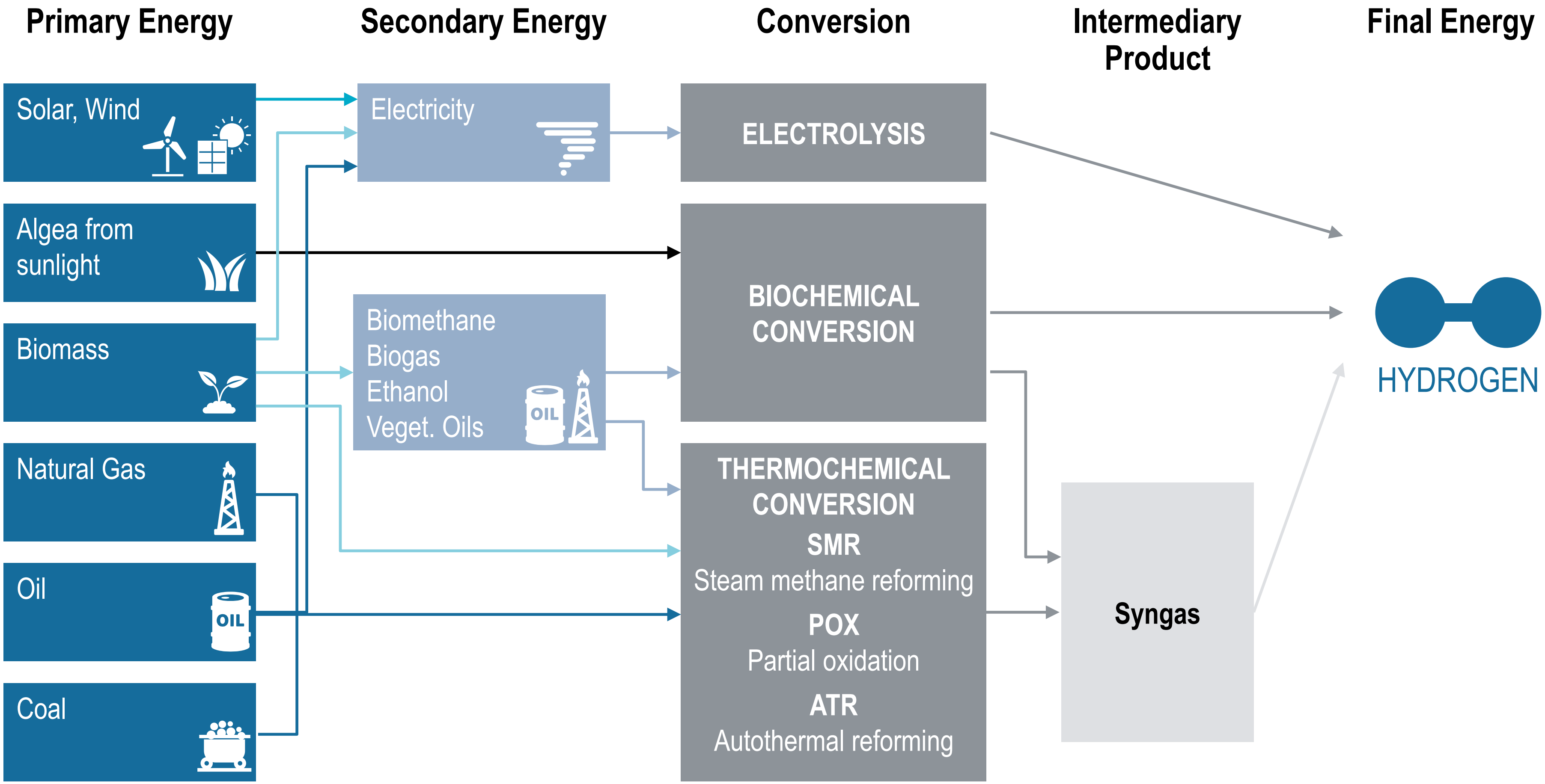
> Please note: cost reductions through the provisions of grid services are not included yet

Source: FCH2 JU, Roland Berger

Recap: in principle, hydrogen can be produced by three major conversion methods

Different hydrogen production methods

Schematic/Simplified



Primary Energy

Secondary Energy

Conversion

Intermediary Product

Final Energy

Solar, Wind

Algea from sunlight

Biomass

Natural Gas

Oil

Coal

Electricity

Biomethane
Biogas
Ethanol
Veget. Oils

ELECTROLYSIS

BIOCHEMICAL CONVERSION

THERMOCHEMICAL CONVERSION

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

Syngas

HYDROGEN

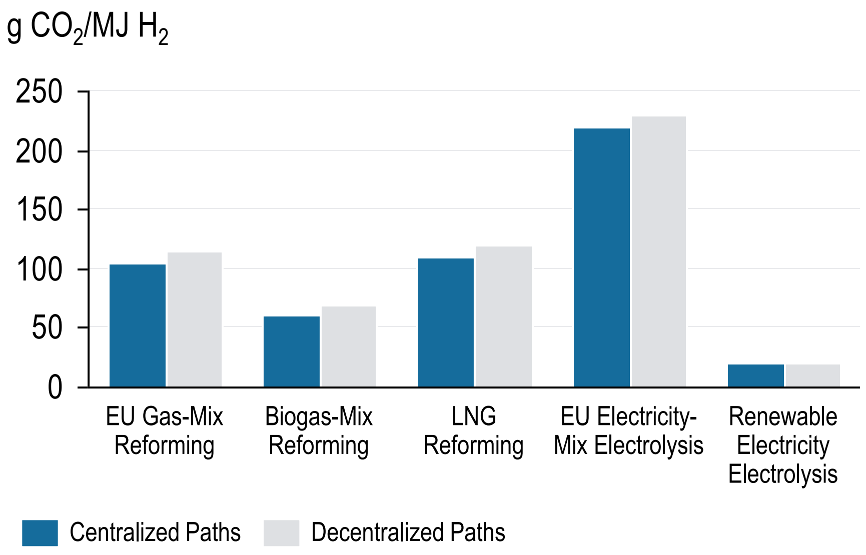
Source: Shell, FCH2 JU, Roland Berger

Green hydrogen might be comparatively more expensive in the short term – Fossil-fuel based H_2 causes higher CO_2 emissions

Comparison of key production methods

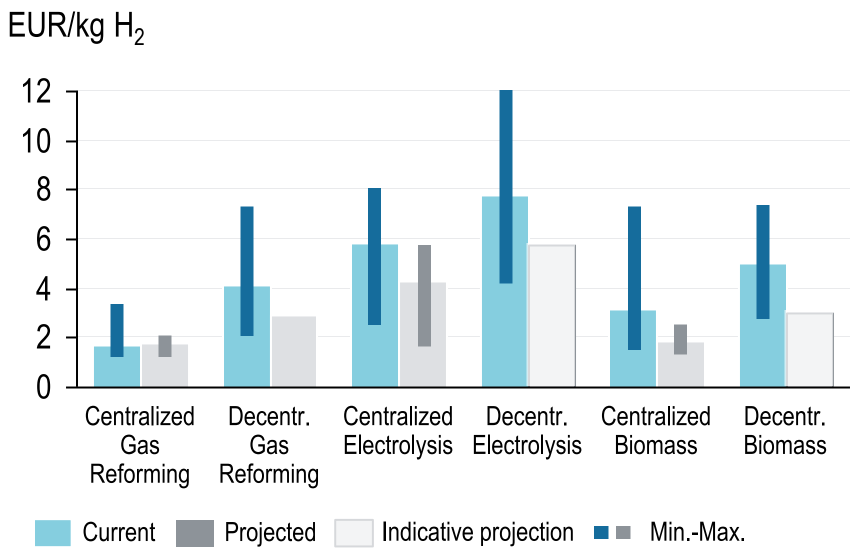
Indicative

CO_2 emissions of hydrogen production



- Attributable CO_2 emissions depend on carbon intensity of underlying fuel mix (natural gas, biogas, electricity)
- Significant regional or supply-chain-related differences within each production method

Cost of hydrogen production[1]



- Production cost differ depending on plant size, capacity utilisation, raw material costs, etc.
- Decentralised gas reforming, centralised electrolysis and centralised biomass pathways in particular are expected to offer further cost-saving potential (esp. dep. on fuel prices, sustainability requirements)

[1] Excl. cost of CO_2 abatement

Source: Shell, FCH2 JU, Roland Berger

CCS could be an alternative technology to "decarbonise" grey hydrogen from SMR, at higher total production cost

Excursus: SMR with Carbon Capture and Storage (CCS)

> SMR is the leading technology for hydrogen production from natural gas or light hydrocarbons. Reductions of CO_2 emissions beyond the efficiency-based minimum would only be possible by the integration of Carbon Capture and Storage (CCS)

> Several technical options exist for capturing CO_2 from an SMR-based hydrogen plant; the current standard is the is the capture of CO_2 from the shifted syngas using MDEA solvent

> CCS from hydrogen production can actually be a commercial operation, e.g. as supply of industrial and food grade CO_2 to various offtakers

> Adding CCS technology increases both capital cost and operating expenditure of the hydrogen plant (e.g. due to increasing natural gas consumption)

> Recent studies estimate that the Levelised Cost of Hydrogen from an SMR-based hydrogen plant would increase by 18-48% when including CCS technology (i.e. vs. a base case without CCS)

> Please refer to the following recent (and rather technical) study by the IEA's Greenhouse Gas R&D Programme for further information: "Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS" (IEAGHG Technical Report 2017-02, February 2017)

Source: IEAGHG, FCH2 JU, Roland Berger

E.3 Hydrogen injection into the natural gas grid

Injecting (green) H_2 into the gas grid promises 4 key benefits: sector coupling, gas decarbonisation, energy storage and H_2 de-risking

Main potential and value propositions

A. Sector coupling

… allowing for environmental benefits of increasingly **green electricity to spill over to other sectors** that are linked to the natural gas infrastructure, e.g. industrial power/heat, mobility

B. Decarbonising the gas grid

… greening the **gas grid by lowering its carbon intensity (with "admixture" of natural gas and green hydrogen)**, improving the environmental performance of efficient gas-based power and heat generation – a "low-hanging fruit" for decarbonisation

Injecting green hydrogen into the natural gas grid

… enabling the **de-coupling of variable energy supply from renewables and energy consumption**, by using the existing natural gas transmission, distribution and storage infrastructure

C. Energy storage

> Offering power-to-hydrogen operators **a complementary value stream** to de-risk potential initial demand shortfalls from industrial or mobility off-takers

D. Risk mitigation

Source: FCH2 JU, Roland Berger

For the business case, regulatory framework, additional cost and monetisation options have to be considered

Key elements of the business case

1. Regulatory framework

> Maximum blend level / hydrogen injection limit

> Additional regulatory requirements

2. Additional cost

> Cost of injection equipment (CAPEX, OPEX)

> Allocation of cost betw. operator and gas TSO/DSO

3. Monetization / revenue streams

> Biomethane feed-in-tariff (FIT) regimes

> Competition with natural gas, biomethane (possibly under carbon penalty regime)

4. Specific use case

> Size, technology, etc.

> Injection level – TSO vs. DSO

> Stand-alone injection vs. combination with other green H_2 production purpose

Overall business case assessment

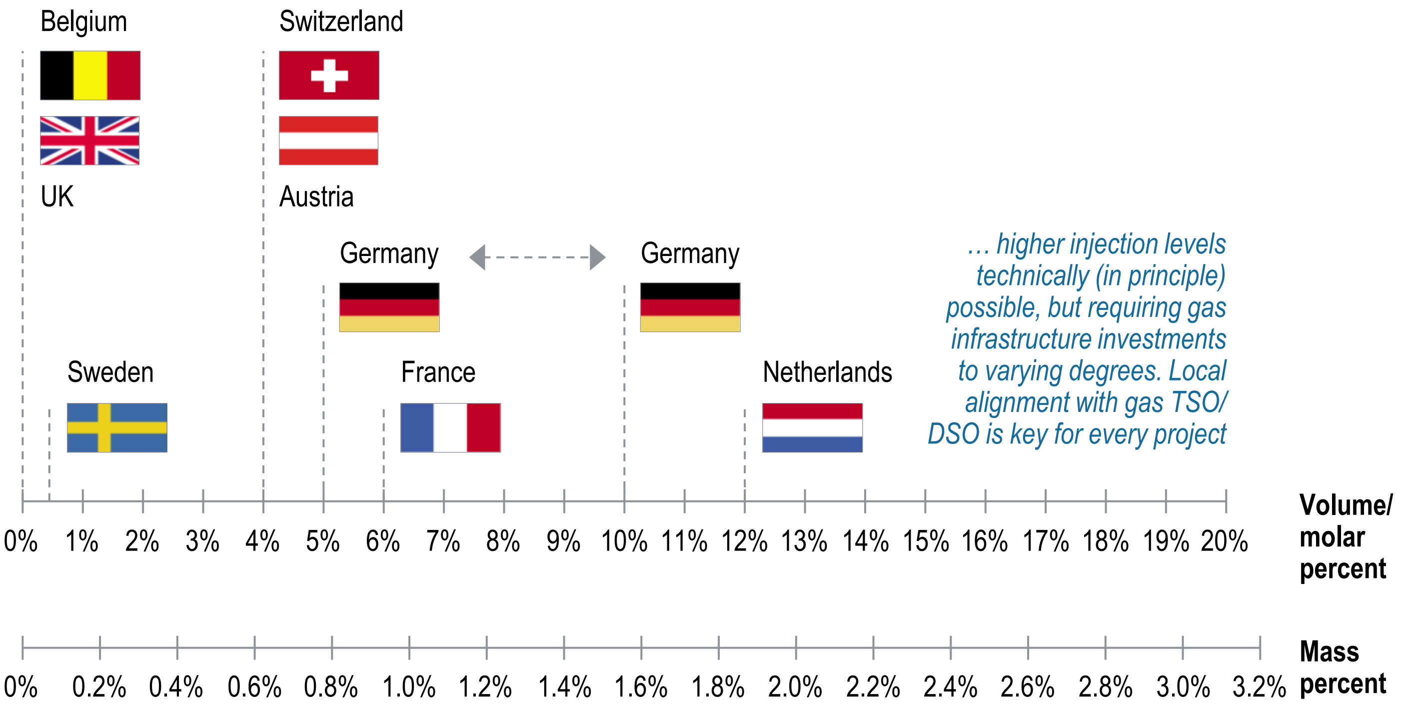
> NPV, payback period, etc. as economic decision-making criteria

> Key drivers and sensitivities

Source: FCH2 JU, Roland Berger

The maximum (local) blend level of hydrogen into the gas grid varies greatly across (and even within) European countries

#1 – Regulatory framework, esp. maximum blend level / H_2 injection limit



… higher injection levels technically (in principle) possible, but requiring gas infrastructure investments to varying degrees. Local alignment with gas TSO/ DSO is key for every project

- Regulatory injection limit varies greatly across Europe and even within countries (e.g. local limits in Germany of $2\%_{vol}$ in case of presence of downstream CNG refuelling stations or storage (e.g. underground)
- CEN and EASEE-gas are working toward a harmonized standard for gas quality in the EU. Due to the type II vessels for CNG vehicles, $2\%_{vol}$ hydrogen tolerance in the gas mix is the current basis for discussion
- Higher H_2 blend levels might require add. pipeline monitoring/maintenance measures (gas TSO/DSO); degrading durability of metal pipes and materials when exposed to hydrogen may also necessitate infrastructure upgrades

Source: Hinico, Tractebel ENGIE, ITM Power, FCH2 JU, Roland Berger

Direct injection requires add. CAPEX and OPEX on site, dep. on national/local context – Add. cost of injection are relatively small

#2 – Add. cost components of hydrogen injection interface – INDICATIVE

Key add. cost elements

Current focus

Gas distribution grid	**2017**	**2025**
Pressure	10 bar	
CAPEX injection station	EUR 600 k	EUR 480 k
OPEX [% CAPEX]	8%	
Lifetime	35 years	

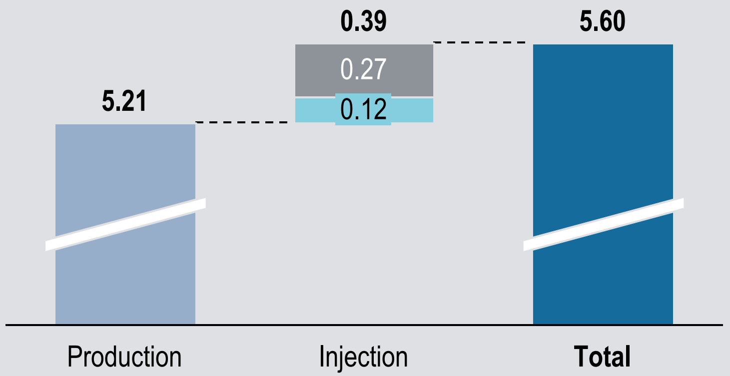
Gas transmission grid	**2017**	**2025**
Pressure	60 bar	
CAPEX injection station	EUR 700 k	EUR 560 k
OPEX [% CAPEX]	8%	
Lifetime	35 years	

CAPEX H_2 connection piping	EUR 300 k/km
CAPEX H_2 equipment	EUR 200 k
OPEX [% CAPEX]	EUR 200 k

Example for effective cost of injection

> **Key assumptions <u>of this example</u>**: 5 MW PEM (at 2017 parameters); 2,500 FTE with full injection; 30 EUR/MWh average electricity cost; DSO-level injection; 250 m piping

> **Cost of injecting H_2 into the gas grid** [EUR/kg]:



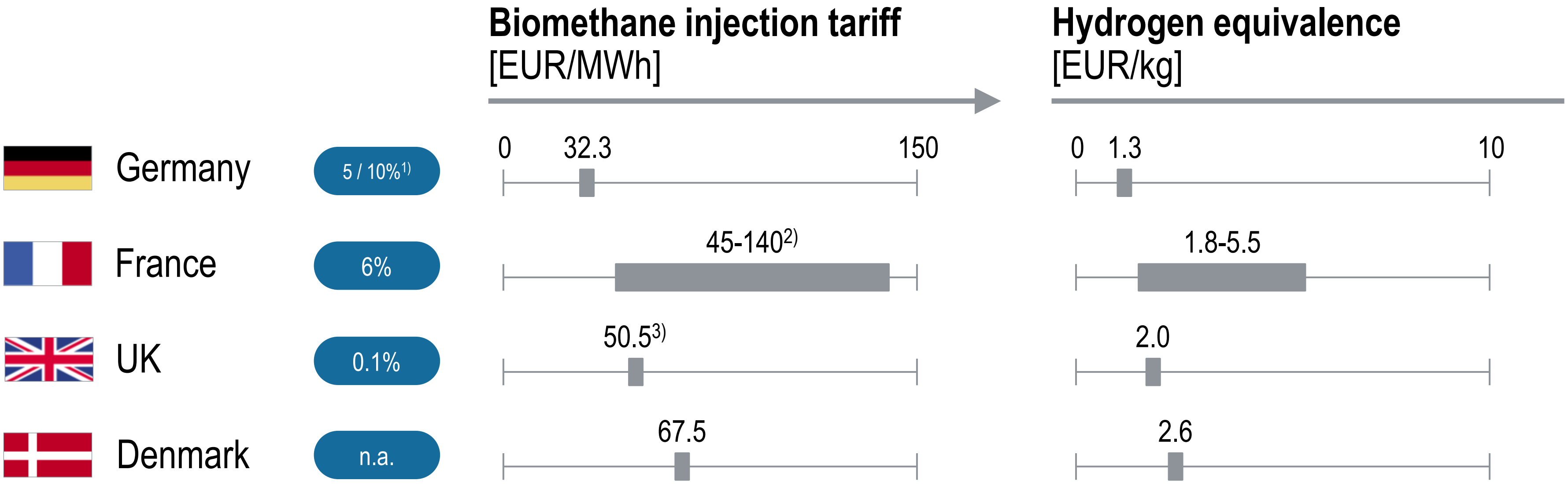
> **Please note:** Cost dynamics change with regards to e.g. size of electrolysers, technology, operating hours, share of hydrogen injected vs. share that is monetised otherwise

■ OPEX injection ■ CAPEX injection ■ Hydrogen production

Source: Hinico, Tractebel ENGIE, FCH2 JU, Roland Berger

Short-term monetisation may come via biomethane FIT, long-term competition with CO_2-penalised natural gas conceivable

#3 – Monetization / revenue streams, esp. equivalence to biomethane injection



		Biomethane injection tariff [EUR/MWh]	**Hydrogen equivalence** [EUR/kg]
Germany	5 / 10%[1]	32.3	1.3
France	6%	45-140[2]	1.8-5.5
UK	0.1%	50.5[3]	2.0
Denmark	n.a.	67.5	2.6

- The injection of green hydrogen into the gas grid decreases the carbon footprint of natural gas and should thus be eligible for feed-in tariffs in line with supporting regimes for biomethane
- In the long run, it is conceivable that an effective carbon price is introduced that would apply (among others) on natural gas, thereby mechanically reducing the cost gap between green hydrogen, biomethane and natural gas

● Hydrogen injection limit

1) <2% vol. in some conditions 2) 2015 3) 2016

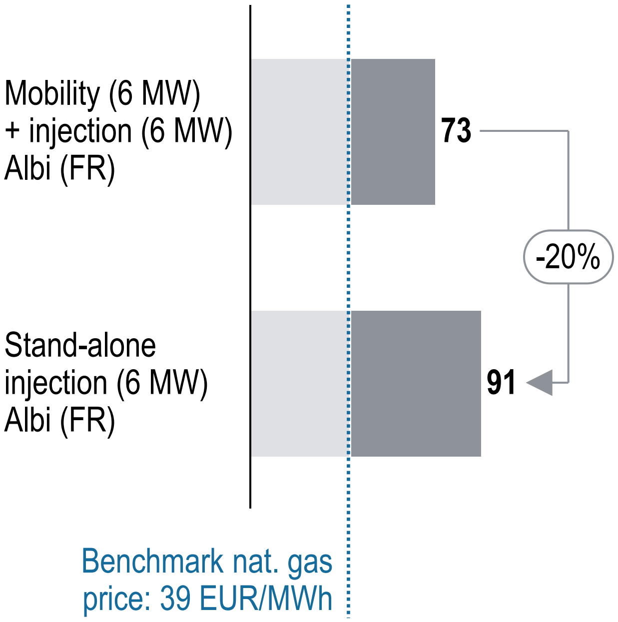
Source: Hinico, Tractebel ENGIE, FCH2 JU, Roland Berger

Significant feed-in tariffs are necessary to allow for a profitable investment – Stand-alone business cases are generally difficult

Overall preliminary business case assessment – 2 INDICATIVE EXAMPLES[1]

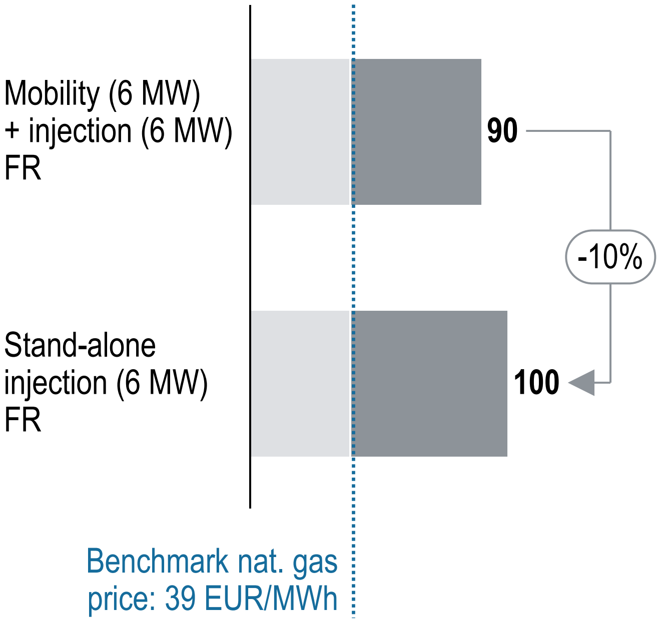
Requ. FIT with pay-back time of 8 years
(with electricity discount)

Injection tariff (EUR/MWh)



Requ. FIT with pay-back time of 8 years
(without electricity discount)

Injection tariff (EUR/MWh)



- Significant FITs are necessary for profitable investments in hydrogen injection
- Combining injection with hydrogen sales to mobility or industry users reduces the level of the required FIT
- Most of the electrolyser capital cost is paid by mobility or industry clients; injection tariff only needs to cover marginal injection costs (and very limited injection-specific CAPEX).
- Here: in case the stand-alone injection business case only receives a FIT of 73 EUR/MWh, payback time will double to >16 years
- H_2 injection might thus be best considered as a secondary application

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1) Comparing two specific scenarios in France for the target year 2025 , with and without access to discounted electricity

Source: Hinico, Tractebel ENGIE, FCH2 JU, Roland Berger

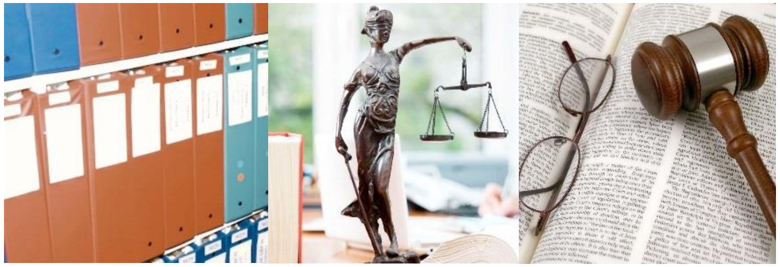
Gas grid injection can be a key enabler of other power-to-hydrogen applications – if and when the right policies are in place

Key additional considerations

1 Combined use cases and business cases: "X plus gas grid injection"

- Gas grid injection can be a complementary application that has the potential to increase the revenues of an electrolyser used e.g. for mobility or industry
- It could help mitigate the risk of lower-than-expected mobility demand ("valley of death") covering the operation costs and part of asset depreciation towards break-even

2 Key success factor from a policy-making perspective: recognition



- Power-to-hydrogen electrolysers can provide gas with low carbon intensity
- Policy makers can provide a level playing field for the injection of carbon lean gas into gas grid, be it biomethane or green hydrogen
- Green hydrogen should be recognized as "compliance option" to reduce carbon intensity of conventional fuels

Source: Hinico, Tractebel ENGIE, FCH2 JU, Roland Berger

Regions and cities can identify suitable locations for power-to-hydrogen projects with gas grid injection along 4 main criteria

What to look for in identifying power-to-H_2 projects **with gas grid injection** …

✓ **1. Local grid challenges with growing renewables capacities**

- > Increasing wind and solar capacities
- > (Distribution) grid constraints, e.g. due to low interconnectivity – rising congestion challenges, possible needs for curtailment

✓ **2. Intersections of gas and electricity distribution grids**

- > Urban / suburban areas with RES feeding into MV electricity distribution grid and medium-/low-pressure gas grids for residential/commercial gas supply

✓ **3. Sufficiently high hydrogen injection limits for the local gas grid**

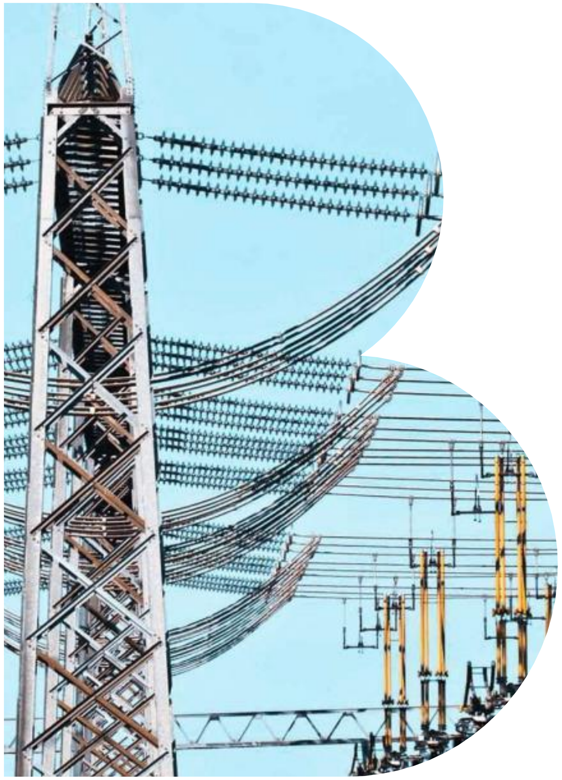
- > Hydrogen injection levels of e.g. $2\%_{vol}$ or more permitted acc. to local regulation

✓ **4. Monetisation options for green hydrogen – in gas grid and otherwise**

- > Primary monetisation / value stream, e.g. hydrogen supply to mobility users
- > Plus existing regime for biomethane injection accessible for green H_2 (or bespoke regional remuneration schemes, e.g. green-H_2-gas admixture remuneration)

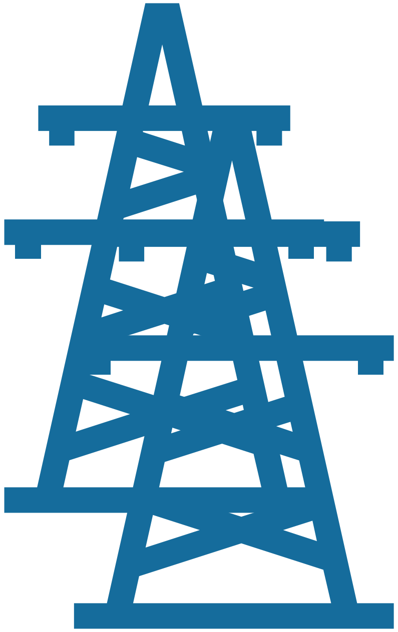
Source: FCH2 JU, Roland Berger

E.4 Electricity grid services from electrolysers



Electrolysers offer strategic value to an electricity grid that increasingly requires balancing – Add. revenue streams for green H_2

Main potential of electrolysers in the context of grid balancing services



> **With growing shares of renewables in the electricity mix, strategic opportunities for electrolysers are expected to grow as well,** mainly through the more frequent (timely and spatial) convergence of …
- Decreasing marginal cost of electricity
- Increasing need for flexible loads for grid balancing services / higher willingness to pay for load flexibility

… **resulting in overall reduced cost of production for green hydrogen**

> By shifting (in advance or in delay) from a planned hydrogen production schedule, **electrolysers can adapt its electricity consumption to variable RES production** – and thus provide grid balancing services

> **Electrolysers can provide <u>low/zero-carbon demand-side grid services</u>** (as secondary revenue stream) – i.e. as new type of "negative load" in the system – vs. supply-side grid services that are currently dominating the grid service markets

> **Regional differences matter**, when considering electrolysers as grid service providers :
- Systemic need for balancing grids (and type of balancing services) – e.g. dependent on interconnectivity, scale and type of renewables installed
- Market mechanisms as shaped by (national) regulations, product definition, procurement rules, technical requirements and remuneration

Source: FCH2 JU, Roland Berger

In principle, electrolysers are technically capable for all three major types of electricity grid services

Typology of 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 (only tested under lab conditions until now)	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

Activation time; operating time

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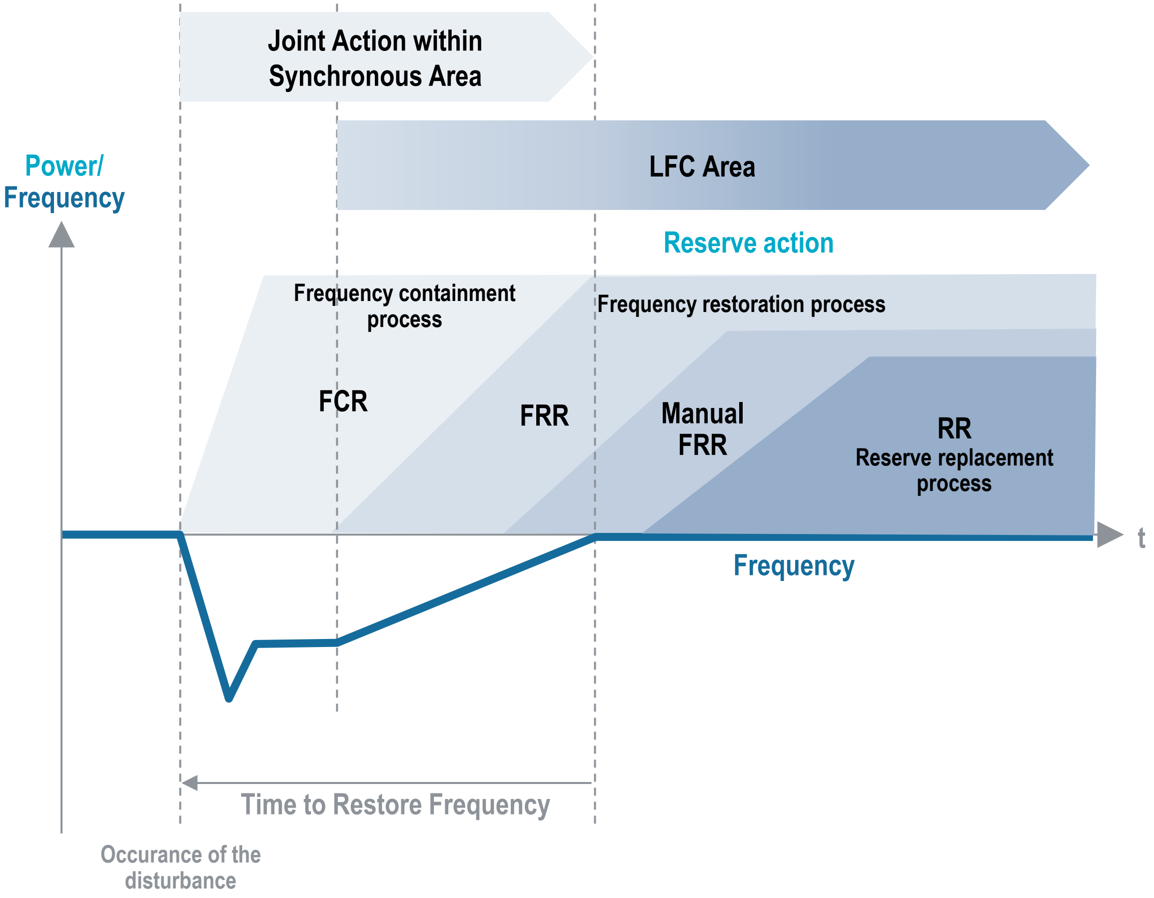
1) Based on regulation in Continental Europe; power grid frequency of 50.00 Hz 2) Dependent on regulation and requirements in each country

Source: FCH2 JU, Roland Berger

The market for grid services presents a significant, albeit secondary, business opportunity

Typology of electricity grid services by activation sequence



- **Total market for load frequency services is closely correlated to the size of the power sector** of a country, e.g. in Germany roughly 5 GW of services are procured, i.e. ca. 6% of peak demand
- **FCR** is activated within max. 30 seconds (during the frequency containment regulation process) to contain frequency changes caused by a disturbance. It is followed by the activation of **FRR** to restore the frequency to 50 Hz and later replaced by the slower **RR** so that FCR resources are disengaged and again available to tackle potential new disturbances
- **Market is heavily determined by national regulation** for electricity sectors

Source: ENTSO-E, FCH2 JU, Roland Berger

Regulation is largely national; allocation and remuneration schemes (and thus expected revenues) vary from country to country

Regulation and remuneration

Example: FCR remuneration in 2015 – 2016

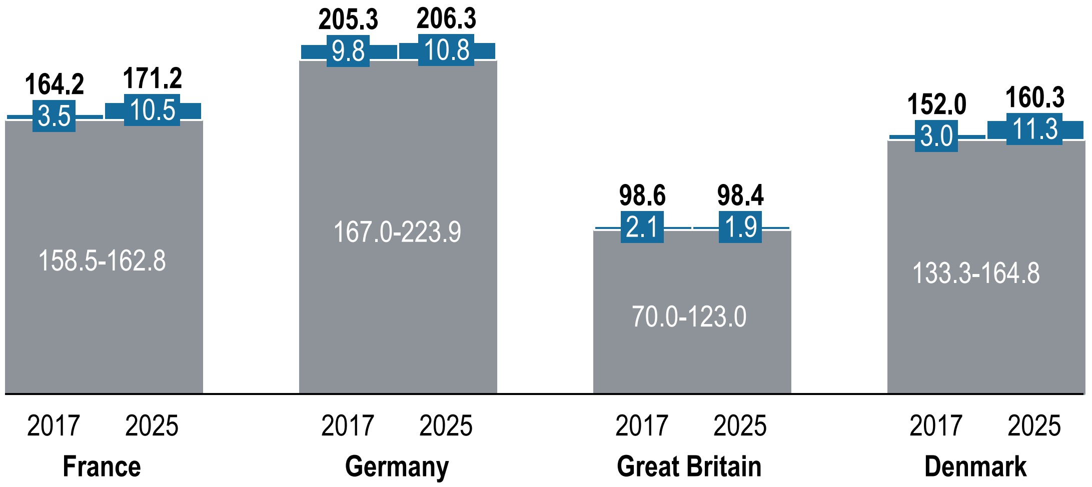
- **Grid services regulation comprises for example**:
  - Procurement forms, e.g. organised market ("auctions") vs. mandatory provision
  - Forward and commitment periods, e.g. week ahead and 1 week respectively
  - Product type, e.g. symmetrical vs. asymmetrical (re. upward/downward load)
  - Minimum bid sizes, e.g. 1 MW
- **Remuneration is typically offered on a capacity basis** or (capacity + energy activated, settlements occur e.g. based on "pay-as-bid" or regulated prices)
- **Thus, the revenue potential from grid services critically depends on the location of the electrolyser** (and hence the reduction of the effective cost of green hydrogen production)

Source: Hinico, Tractebel ENGIE, FCH2 JU, Roland Berger

Grid services can bring in significant revenues, but electrolysers will look to other H_2 monetisation options as primary source of income

Electrolysers and the economics of grid services

Hypothetical example: expected income from a 1 MW PEM electrolyser [k EUR / MW / year][1]



> Assuming no conflicts of usage with primary monetisation options (e.g. hydrogen sales to mobility or industrial users)

> Focus on PEM technology due to ability to supply frequency services with fast reaction times (full activation < 30 sec)

🟦 Balancing (15 EUR/MWh) ▨ Frequency

> **Critical challenge: interoperability** between secondary provision of grid services (i.e. "flexibility") and hydrogen production targets for primary sales, esp. in terms of
- Reaching hydrogen production targets and
- Ensuring cost-efficient production at lowest-possible marginal cost of electricity

> Revenues for **frequency reserve participation** vary with the electrolyser size, technology and operation time, but tend to generally not interfere with the targeted primary hydrogen production – significant revenue potential

> For **balancing services**, interoperability with the supply of hydrogen for primary applications reduces the expectable revenue potential (in this example to less than 50% across all countries and time scenarios), e.g. because of load shifting to operating hours with higher electricity cost, activation prices failing to cover add. cost

> **Thus: focus on frequency services as secondary value stream re. grid services**

> Future and sustained challenges might give rise to add. grid service products that electrolysers can service

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1) Under historical regulation / remuneration, excl. comparatively low revenues from grid services in the distribution grid

Source: Hinico, Tractebel ENGIE, FCH2 JU, Roland Berger

F. Your contacts

Please do not hesitate to get in touch with us

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Source: FCH2 JU, Roland Berger

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50 YEARS

navigating
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