# Prospects and Challenges for Fuel Cell Applications

**Paul Lebutsch**

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# Prospects and Challenges for Fuel Cell Applications

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**ECN**

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Roads2HyCom Research & Technology Workshop, Brussels, 5-6 March 2009

# Prospects and Challenges for Fuel Cell Applications - Overview -

- Objectives
- Analysis Approach
- Economical Analysis
- $CO_2$ Emissions
- Summary

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# Prospects and Challenges for Fuel Cell Applications - Objectives -

- **Characterisation of potential FC/$H_2$ applications**
  - Specifications
  - Boundaries
  - Description of the technology and the markets
  - Anticipation of future developments
- **Economic “Windows of Opportunities”**
- **Global impact on $CO_2$ emissions**
- **Gap analysis**
- **Identification of Research Items**

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# Economic "Windows of Opportunity" and $CO_2$ Emissions
## - Analysis Approach -

- **23 transport and stationary applications – case studies by partners**
  - Reference technology
    - Power
    - Investment & maintenance cost
    - Fuel price & fuel consumption
    - Lifetime
    - Mileage/operating hours
  - FC/$H_2$ technology
    - Power
    - Maintenance cost
    - Fuel consumption
  - Characterisation of markets

# Economic "Windows of Opportunity" and $CO_2$ Emissions - Analysis Approach -

- **Determination of "Windows of Opportunity"**
  - Comparison of reference and $FC/H_2$ costs
    Basis: Total cost per unit service (€/km, €/hr or €/kWh)
- **Cost projections of $FC/H_2$ technology**
  - Economy of Scale for state-of-the-art technology
  - Learning for comparison of future technology
  - System power
- **Comparison of projections with "Windows of Opportunity"**
- **Gap Analysis**
- **Source-to-User $CO_2$ emission factors for reference and $FC/H_2$ tech.**

# Prospects and Challenges for Fuel Cell Applications - Overview -

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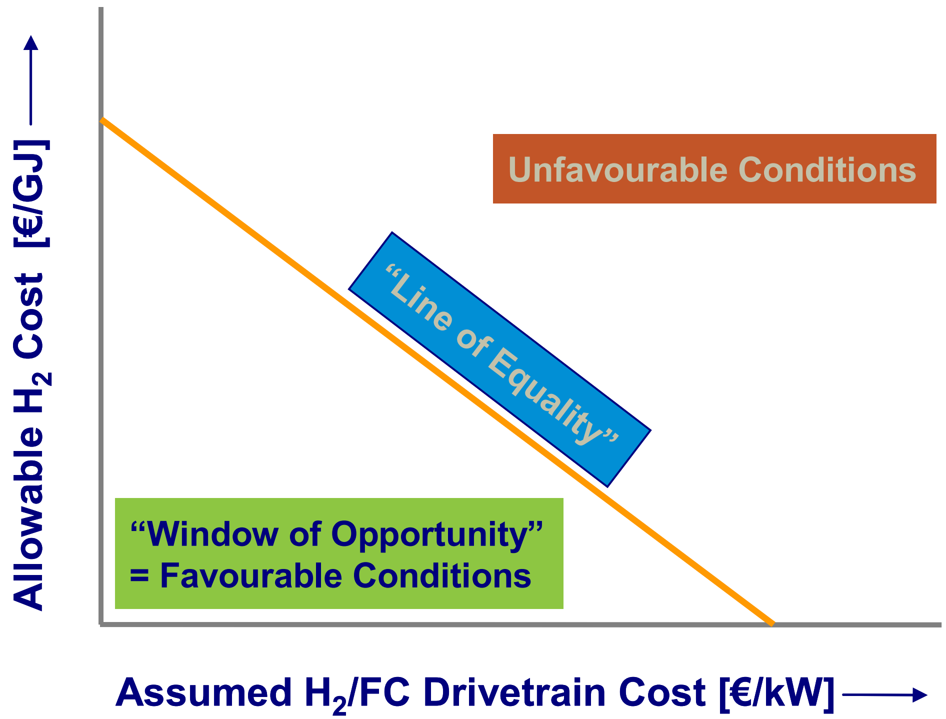
# Economic "Windows of Opportunity" - Methodology -

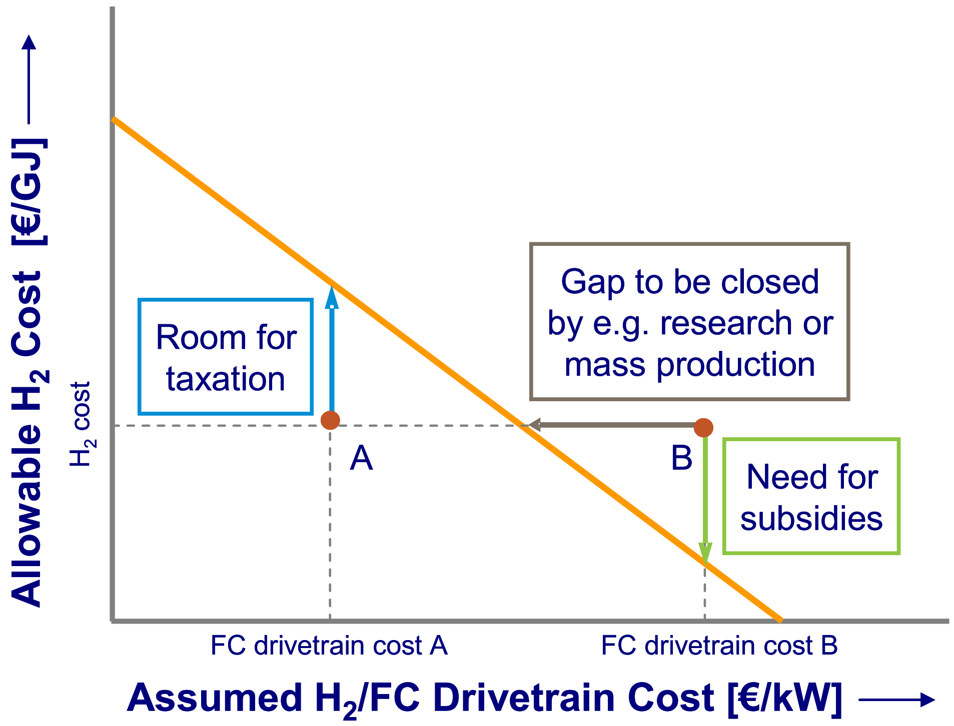



- "Line of Equality":

  Boundary conditions, where reference and FC/$H_2$ technology have equal cost per unit service (€/km, €/hr or €/kWh)

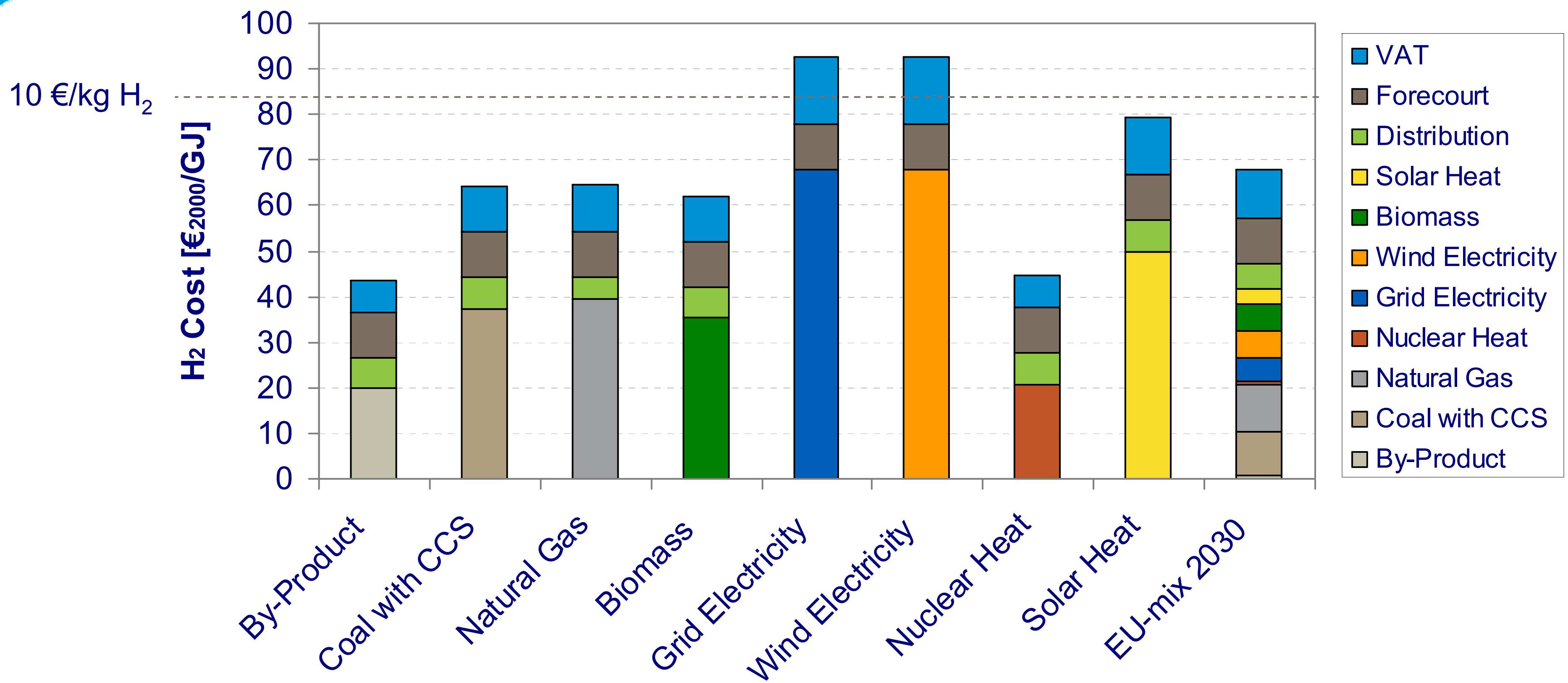
- Projections for hydrogen price and FC/$H_2$ technology costs are plotted and analysed against the Window of Opportunity

# Economic “Windows of Opportunity” - Methodology for Gap Analysis -




- Situation A & B reflect projected cases
- Situation A:
  - Within the “Window of Opportunity”
  - FC/$H_2$ tech. is cost-competitive
  - Difference to “Line of Equality” reflects room for taxation of hydrogen (excise duties)
- Situation B:
  - Outside of the “Window of Opportunity”
  - Unfavourable conditions for FC/$H_2$ technology
  - Enabling cost-competitiveness by:
    - Subsidies on the price of hydrogen
    - Cost reductions of the FC/$H_2$ technology

# Hydrogen Costs used for the - Gap Analysis -




- Projection for EU-Mix 2030 used: 68 $€_{2000}$/GJ or 8,2 $€_{2000}$/kg respectively
- Cost of hydrogen projected by using R2H and HyWays production mix for 2030

**PRELIMINARY RESULTS**

# Prospects and Challenges for Fuel Cell Applications - Overview -

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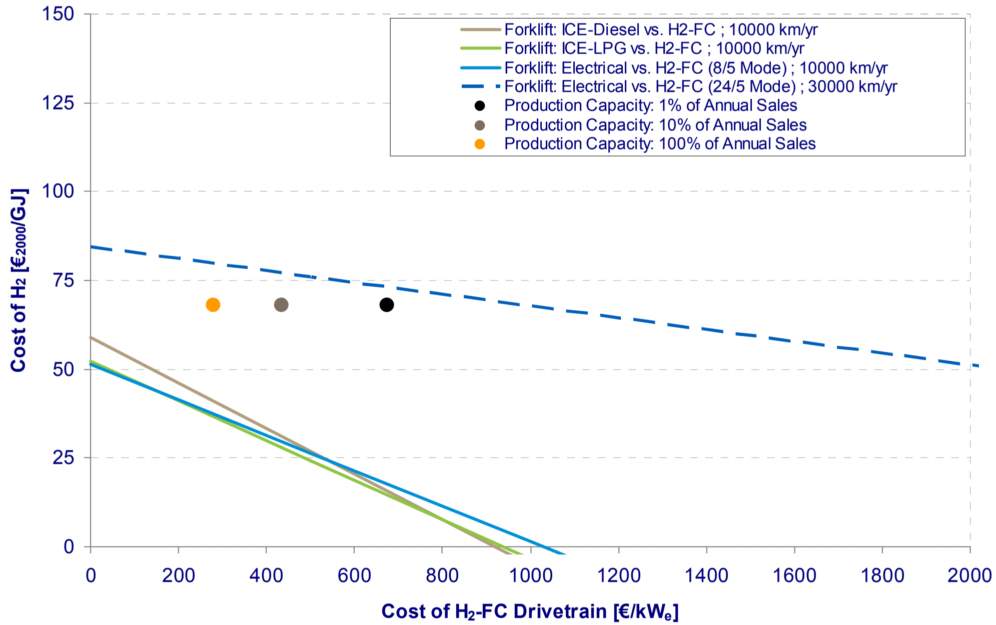
# General Characteristics of favourable Applications

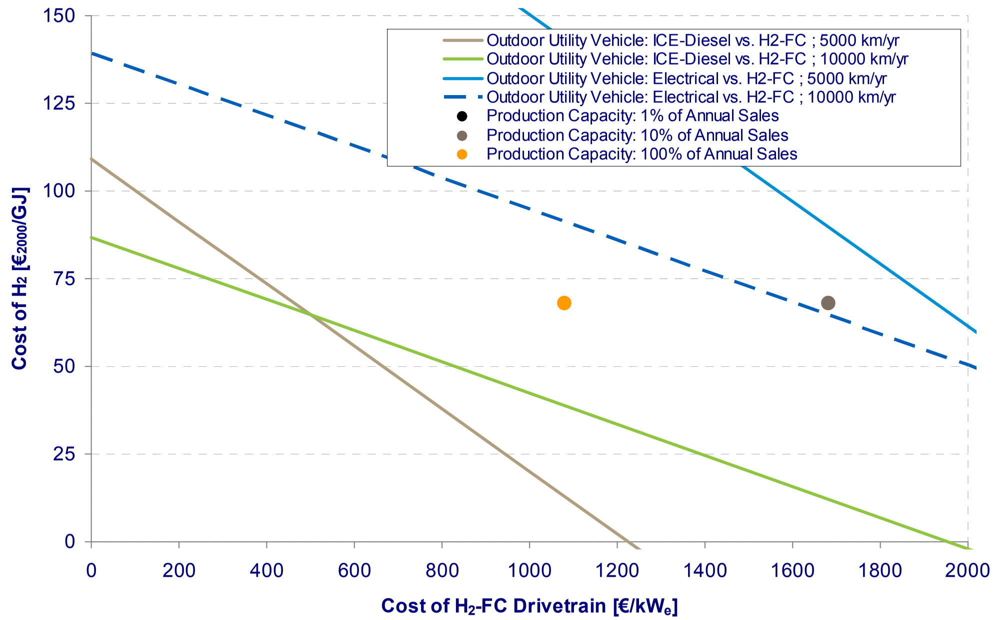
- **Results show general characteristics of favourable applications:**
  - High annual usage (= high impact of FC's high efficiency)
  - Small system power (= low engine investment costs)
  - Low fuel consumption (otherwise price of hydrogen is limiting factor)
- **Replacing battery-electric systems**
  - Reason: Limiting energy-storage capacity of batteries
  - Applications for **near-term markets**:
    - Forklifts in 24/5 operation
    - Outdoor utility vehicles
    - Backup systems (for example for telecommunication systems)

# SOTA Battery-Electric Applications
# - Near-term Market Opportunities -

- Forklifts




- Outdoor Utility Vehicles




- Input parameters: SOTA technologies, 2007 prices and policies
- Data points reflect theoretical production capacities of 1%, 10% and 100% of annual passenger car sales in Europe
- **BUT:** Combined market size is only 200 000 sold units/year

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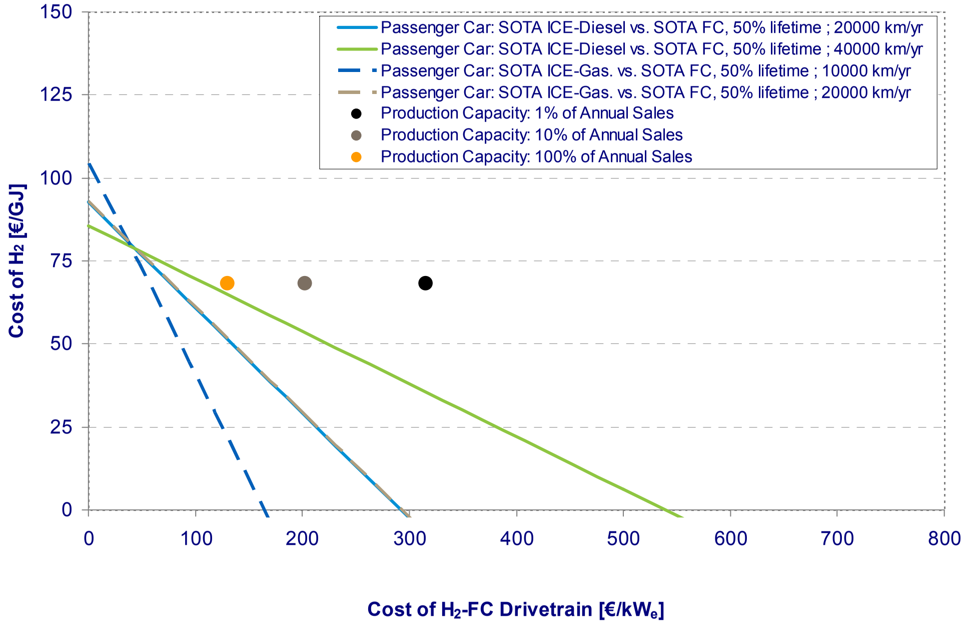
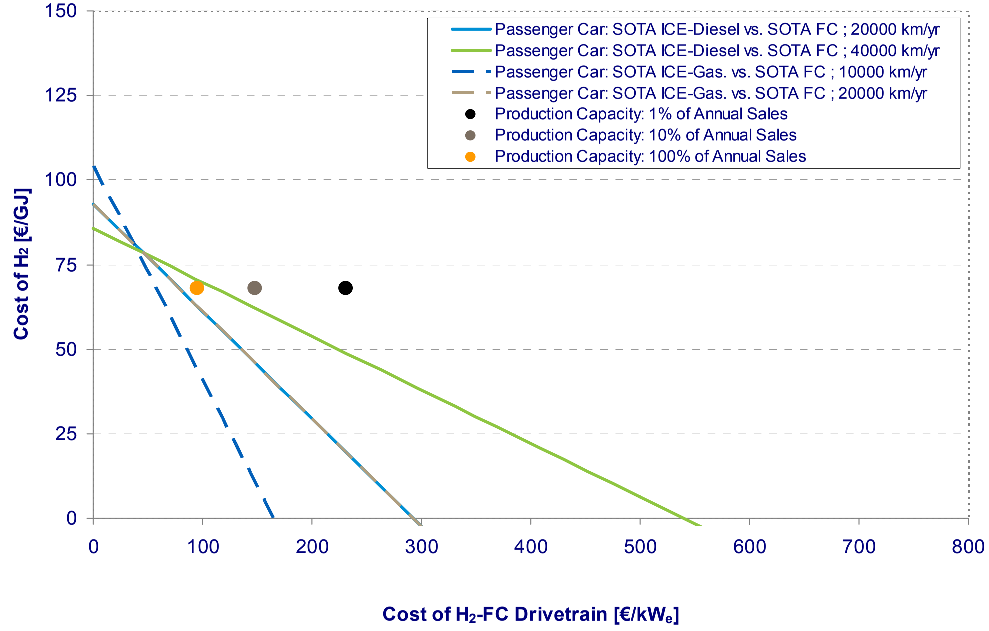
# State-of-the-art Passenger Cars - Influence of Stack Lifetime -

- Lifetime of FC Stack: 50% of application




- Lifetime of FC Stack: 100% of application

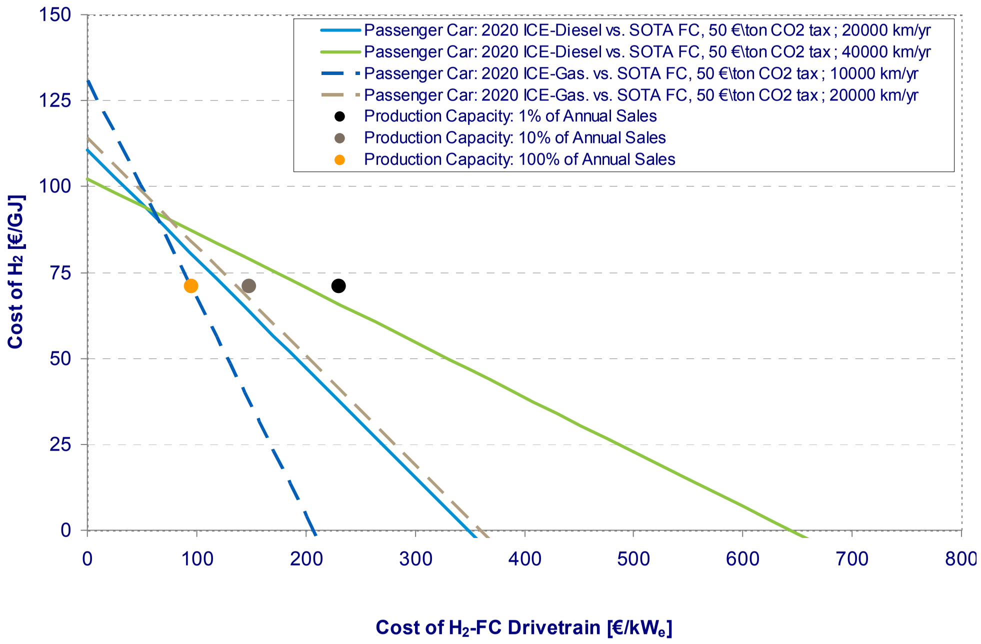


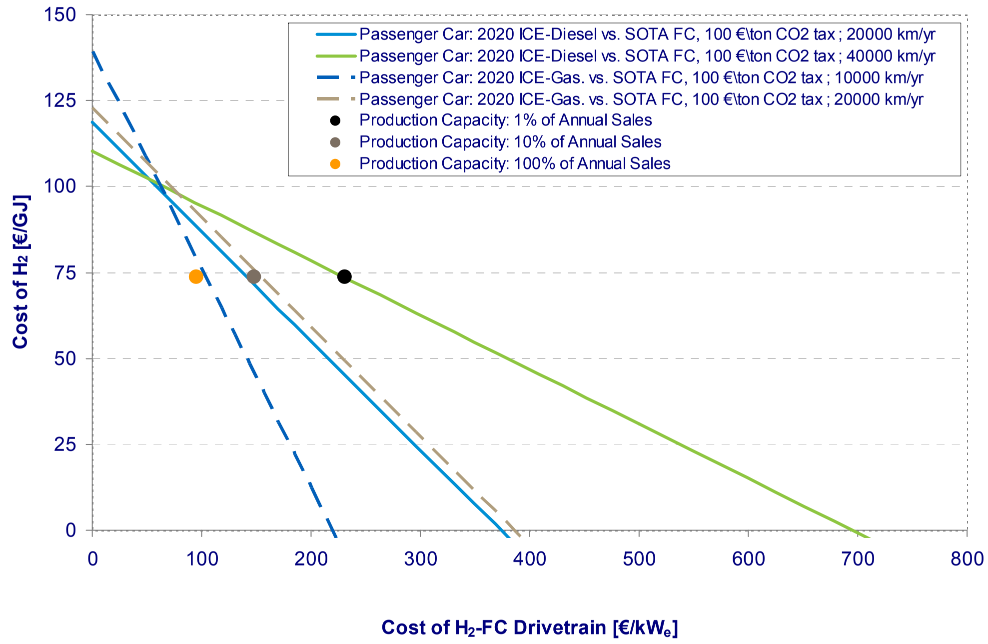

- Input parameters: SOTA technologies, 2007 prices and policies
- Data points reflect theoretical production capacities of 1%, 10% and 100% of annual passenger car sales in Europe
- SOTA technology, even with a stack lifetime equal to the application's lifetime is yet to be developed much further to reduce the cost of the fuel cell drivetrain

**PRELIMINARY RESULTS**

# State-of-the-art Passenger Cars - Influence of $CO_2$ taxation -

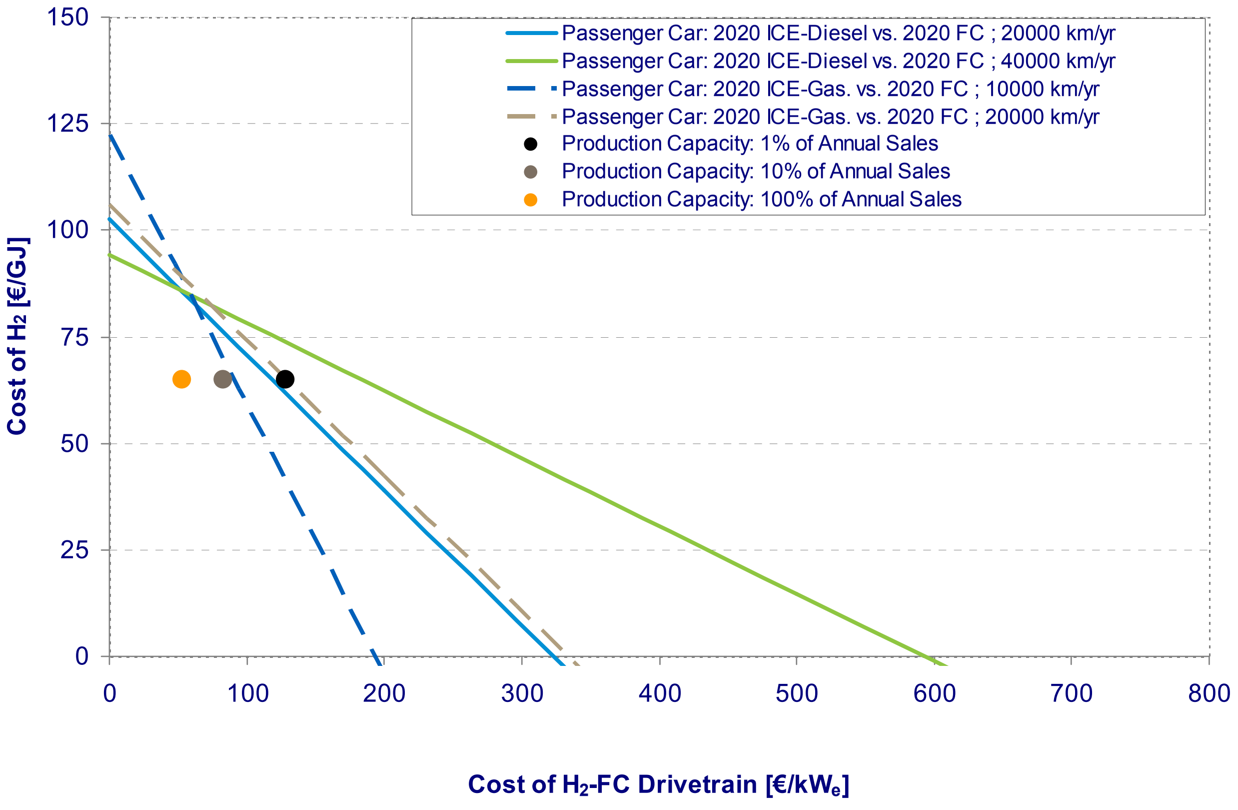
- $CO_2$ tax: 50 €/ton
- $CO_2$ tax: 100 €/ton




- Input parameters: SOTA technologies (stack & technology have equal lifetimes), 2007 prices and policies with additional $CO_2$ tax
- CO2 taxation would influence the Windows of Opportunities towards favouring FC/$H_2$ technologies, if the HyWays production mix for 2030 is assumed

# 2020 Passenger Cars - Promising Outlook -

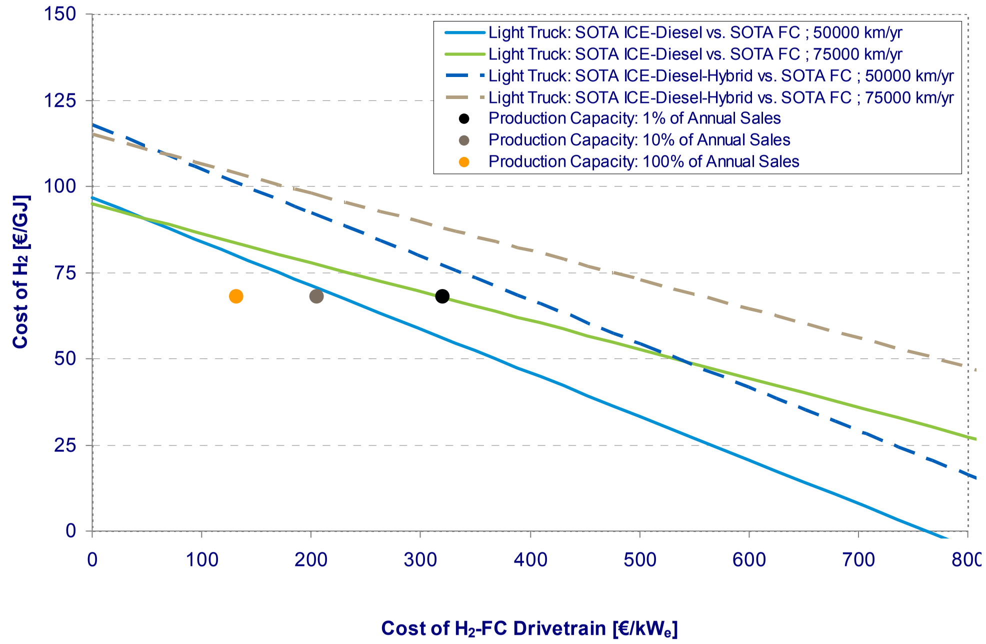



- Windows of Opportunity for passenger cars based on 2020 reference technologies, prices and policies (without $CO_2$ tax)
- The data points reflect 2020 $H_2$-FC specifications assuming equal lifetime of the stack and application
- 2020 $H_2$-FC can compete with reference technologies – but only if economies of scale are realised, learning (research) continues as specified by NREL/TIAX and oil price is >120$/bbl

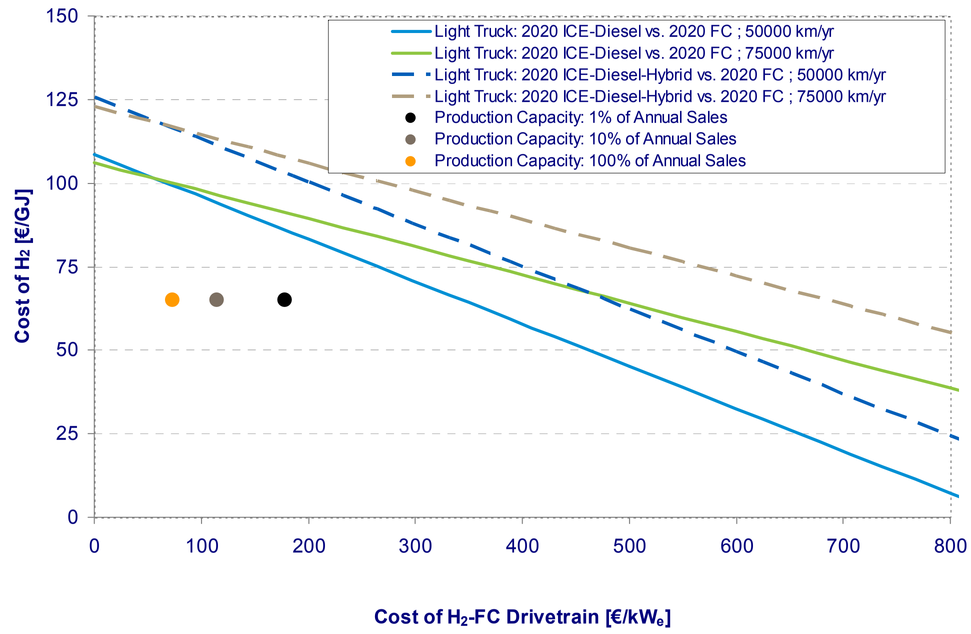
**PRELIMINARY RESULTS**

# Light Duty Trucks
# - Very promising -

- SOTA technologies, 2007 prices and policies




- 2020 technologies, prices and policies




- Light Duty Trucks are an attractive near-term market opportunity
  - High annual mileage, relatively low fuel consumption of medium sized engine
- Market Size: 2 million sold vehicles per year; thus the contribution to economy of scale effects is significant

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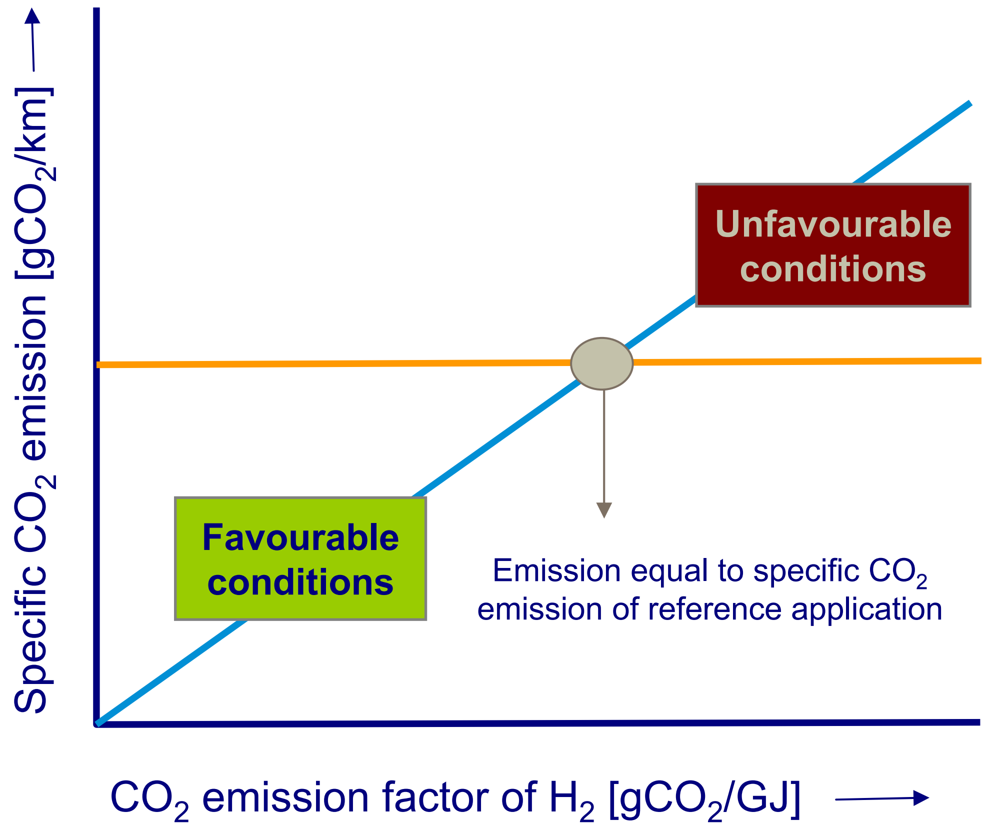
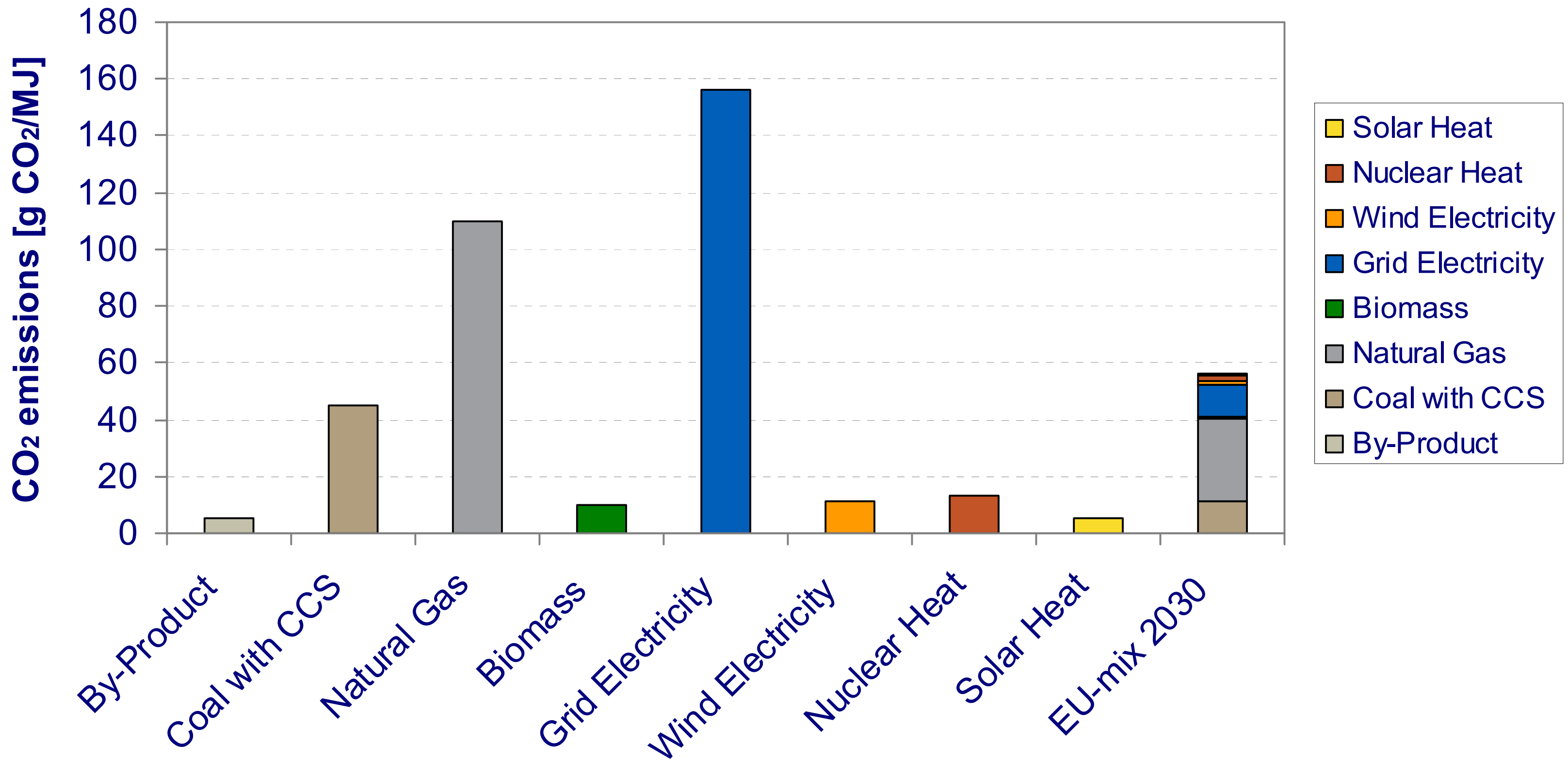
# $CO_2$ Emissions - Methodology -




- Diagonal line: Dependency of $CO_2$ emissions per km/hr/kWh to the $CO_2$ emissions factor for production of the $H_2$ being used in the FC/$H_2$ application
- Horizontal line: $CO_2$ emissions emitted by the application using ref. technologies

**PRELIMINARY RESULTS**

# $CO_2$ Emission Factors for Hydrogen Production




- The $CO_2$ emissions from the different production pathways of $H_2$ and the EU-mix for 2030 from Hyways project based on JRC/EUCAR/CONCAWE well to wheels project
- EU-Mix 2030: 56 $gCO_2$/MJ

# Prospects and Challenges for Fuel Cell Applications - Overview -

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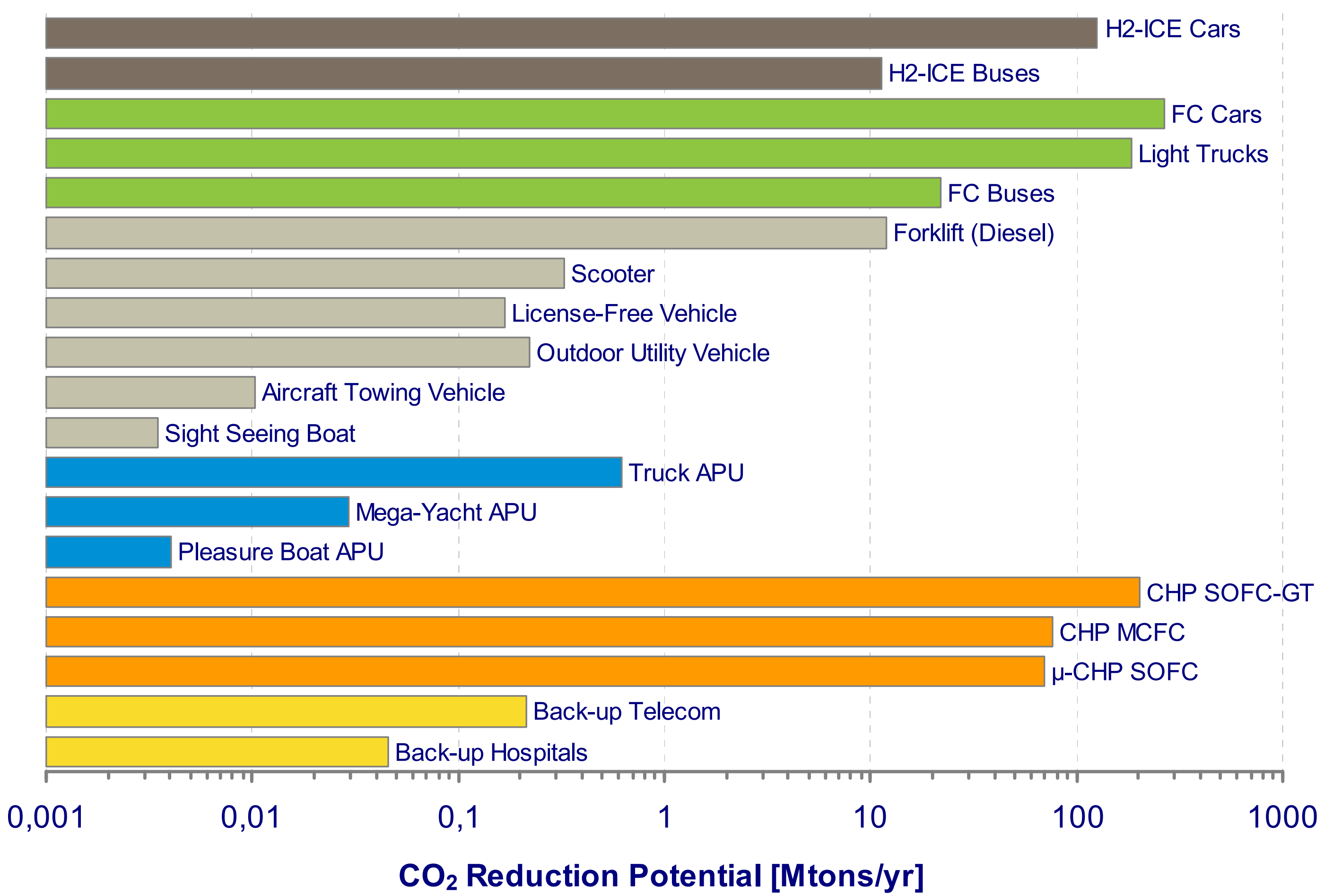
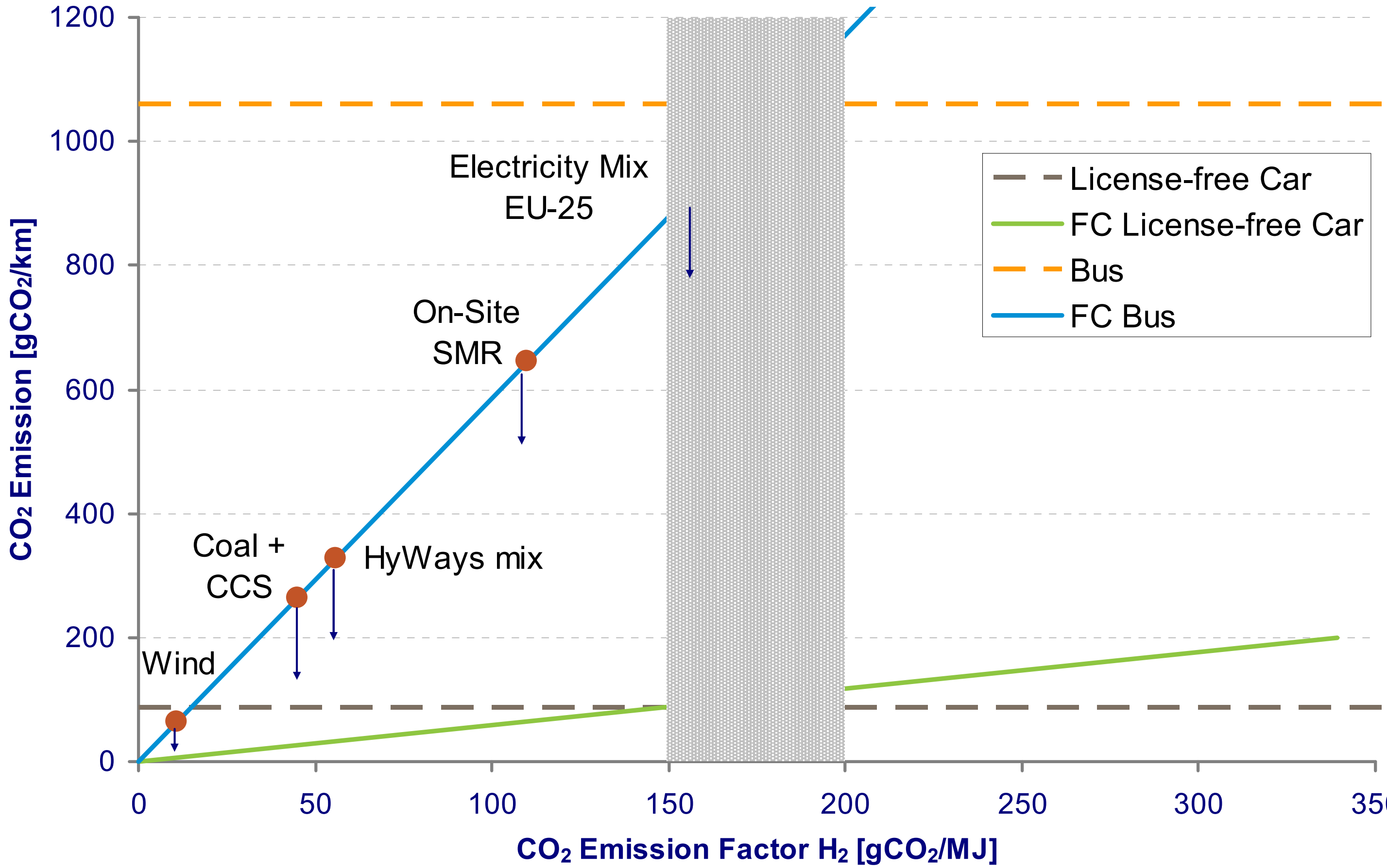
# Total $CO_2$ Emissions Reduction Potential - Mass Markets have highest Impact -




- $CO_2$ Emissions based on HyWays Hydrogen Mix for 2030 & 100% Implementation

PRELIMINARY RESULTS

# $CO_2$ emission reduction depends on $H_2$ emission factor, but many possibilities exist to achieve significant reduction




- Well-to-User emission factors for energy carriers based on EUCAR/CONCAWE/JRC
- $CO_2$ emission reduction depends on hydrogen production technology/fuel source

PRELIMINARY RESULTS

# Prospects and Challenges for Fuel Cell Applications - Overview -

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# Summary
## - Near- and mid-term Markets -

- **Near- and Mid-term market opportunities:**
  - Transport applications:
    - Battery electric forklifts in 24/5 operation and battery-electric outdoor utility vehicles
    - Light duty trucks and passenger cars
  - Stationary applications
    - Hydrogen fuelled back-up power systems e.g. for telecom application
    - Natural gas fuelled commercial and industrial CHP systems (high temperature fuel cells)

# Summary
# - Niche or Mass Markets ? -

- **Product differentiation for early markets or focus on mass market application?**
  - Cost reductions for fuel cells are essential for successful rollouts
  - Economics of scale are one possibility, but require a big market size
  - European market sizes of niche applications are relatively small …
    - Forklifts: 164,000 (share of battery-electric not known)
    - Outdoor utility vehicles: 20,000
    - License-free cars: 35,000
  - … compared to mass market applications …
    - Light duty trucks: 2,000,000
    - Passenger cars: >15,000,000
  - … consequently the contribution of niche markets to cost reductions may be limited
  - Furthermore: Applicability of learning effects not certain

PRELIMINARY RESULTS

## Summary
## - $CO_2$ Emissions -

- **Good prospects for $CO_2$ emission reduction are present even if hydrogen is not completely renewable**
- **Largest $CO_2$ emission reduction potential for**
  - FC passenger cars
  - Light duty trucks
  - Medium sized CHP systems

# Thank You

Acknowledgements

We wish to thank the European Commission for their support under the Sixth Framework Programme as well as all Roads2HyCom project partners for their contributions. Their joint efforts made the Roads2HyCom project and all its subtasks such successful undertakings.

Information on the project is available at www.roads2hy.com

# Prospects and Challenges for Fuel Cell Applications - Overview -

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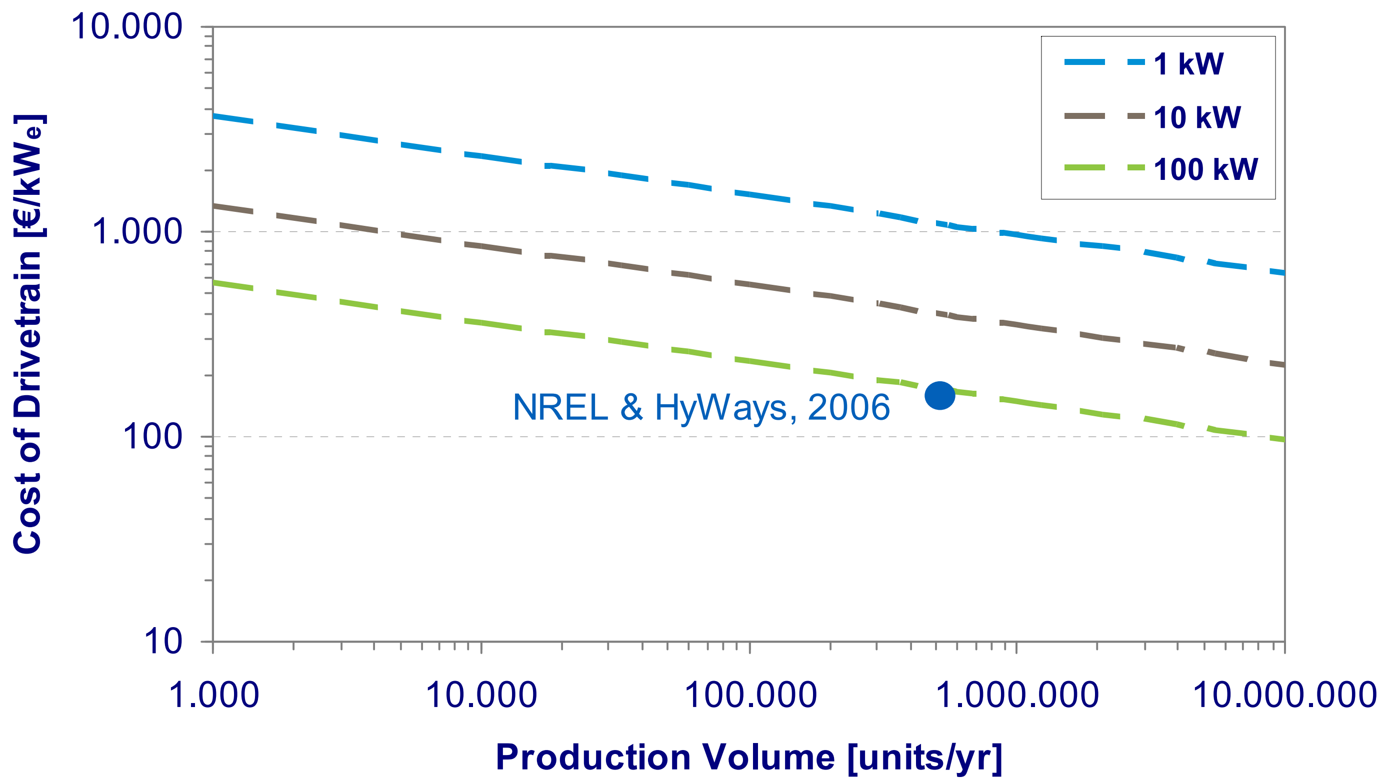
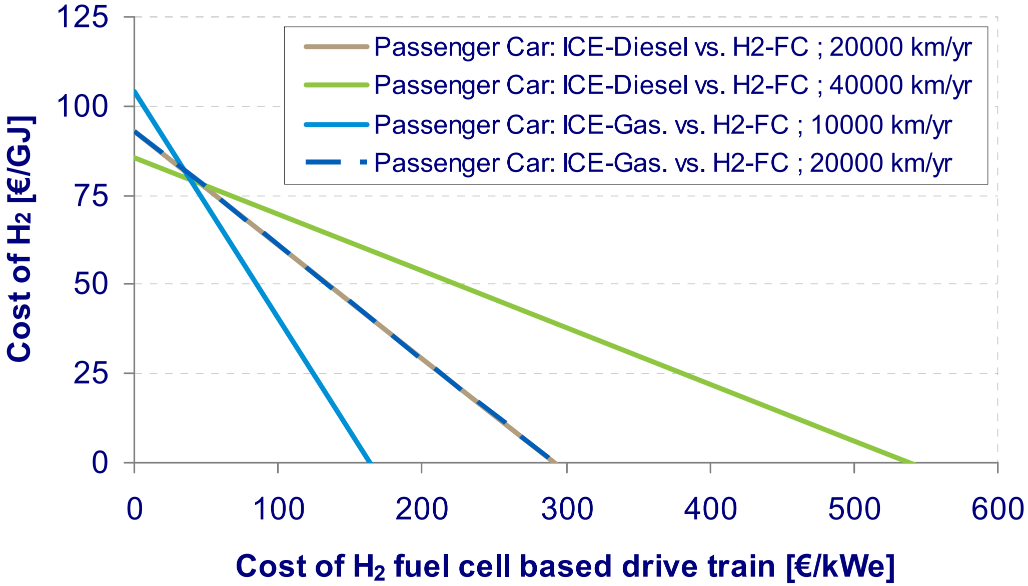
- Economical Analysis
- $CO_2$ Emissions
- Conclusions
- **BACKUP SLIDES**

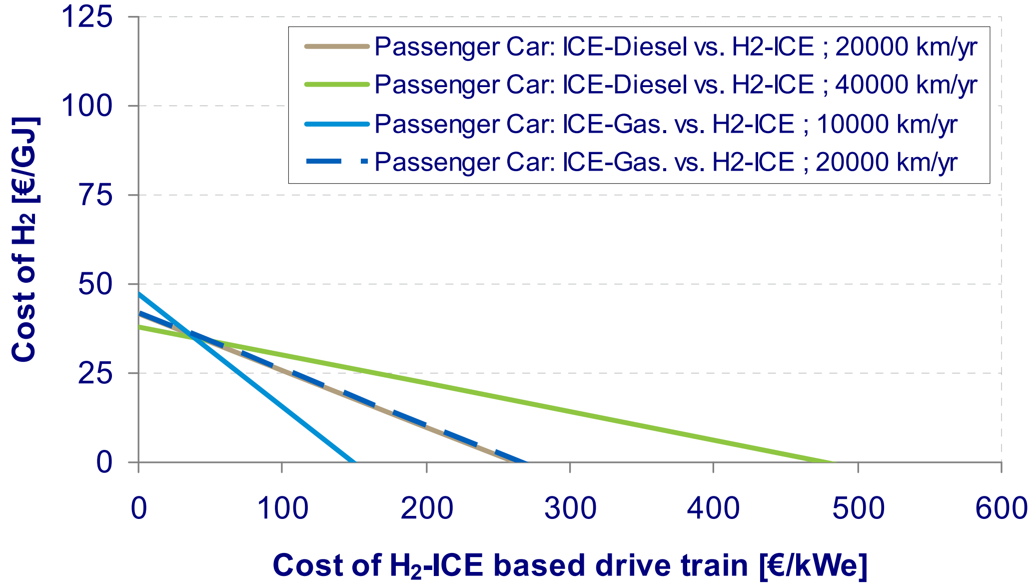
# Economy of scale on drivetrain costs




- FC Drive train includes: FC system, $H_2$ storage, electromotor and battery
- Starting point (NREL, HyWays): State-of-the-art 2005 FC system cost @ 500,000 units/yr
- Effects on cost per $kW_e$: Difference in system power and production capacity

# Comparison of fuel cell and ICE drivetrains operating on hydrogen




- Compared to ICE, fuel cell drivetrains allow about 2x higher cost of hydrogen due to their approximately 2x higher efficiency

# „Windows of Economy“
## - Input parameters reference technology -

| Field of Application (Engine/Fuel) | Power Reference Technology | Energy use | Operational use | Lifetime |
|---|---|---|---|---|
| | kW | MJ/unit | unit/yr | yr |
| Passenger Car (SOTA ICE-Diesel) | 80 | 1,95 MJ/km | 20 000 - 40 000 km/yr | 15 |
| Passenger Car (SOTA ICE-Gasoline) | | 2,02 MJ/km | 10 000 - 20 000 km/yr | |
| Passenger Car (2020 ICE-Diesel) | | 1,56 MJ/km | 20 000 - 40 000 km/yr | |
| Passenger Car (2020 ICE-Gasoline) | | 1,67 MJ/km | 10 000 - 20 000 km/yr | |
| Bus (SOTA ICE-Diesel) | 220 | 12,20 MJ/km | 50 000 - 60 000 km/yr | 15 |
| Bus (SOTA Diesel Hybrid) | | 10,70 MJ/km | | |
| Bus (2020 ICE-Diesel) | | 9,76 MJ/km | 50 000 - 60 000 km/yr | 15 |
| Bus (2020 Diesel Hybrid) | | 8,99 MJ/km | | |
| Light Truck (SOTA ICE-Diesel) | 95 | 2,05 MJ/km | 50 000 - 75 000 km/yr | 15 |
| Light Truck (SOTA Diesel Hybrid) | | 1,80 MJ/km | | |
| Light Truck (2020 ICE-Diesel) | | 1,64 MJ/km | 50 000 - 75 000 km/yr | 15 |
| Light Truck (2020 Diesel Hybrid) | | 1,51 MJ/km | | |
| Licence-free Vehicle | 4 | 1,06 MJ/km | 5000 - 15 000 km/yr | 15 |
| Outdoor Utility Vehicle (ICE-Diesel) | 4 | 1,24 MJ/km | 5000 - 10 000 km/yr | 15 |
| Outdoor Utility Vehicle (Electric) | | 0,31 MJ/km | | |
| Scooter (ICE-Gasoline) | 7 | 0,81 MJ/km | 5000 - 10 000 km/yr | 10 |
| Scooter (Electric) | | 0,2 MJ/km | | |
| Forklift (ICE-Diesel) | 45 | 13 MJ/km | 10 000 km/yr | 10 |
| Forklift (ICE-LPG) | 39 | 13 MJ/km | | |
| Forklift (Electric 8/5) | 20 | 2 MJ/km | | |
| Forklift (Electric 24/5) | | 2 MJ/km | 30 000 km/yr | |
| Aircraft Tow Truck (ICE-Diesel) | 75 | 80 MJ/hr | 1400 - 2800 hr/yr | 10 |
| Aircraft Tow Truck (Electric) | | 10 MJ/hr | | |
| Sightseeing Boat (ICE-Diesel) | 67 | 61 MJ/hr | 959 - 1900 hr/yr | 10 |
| Sightseeing Boat (Electric) | 16 | 14,9 MJ/hr | | |
| Truck APU (ICE-Diesel) | 200 | 149,4 MJ/hr | 500 hr/yr | 10 |
| Pleasure Boat APU (ICE-Diesel) | 2 | 2,25 MJ/hr | 720 hr/yr | |
| Mega-Yacht APU (ICE-Diesel) | 500 | 4885 MJ/hr | 3000 hr/yr | 12 |
| Back-up Telecom (Electric) | 1,1 | 4 MJ/kWh | 56 hr/yr | 10 |
| Back-up Hospitals (ICE-Diesel) | 200 | 10,5 MJ/kWh | 56 hr/yr | 15 |
| Industrial CHP (Natural Gas) | 250 | 9 MJ/kWh | 8760 hr/yr | 5 |
| Residential CHP (Boiler) | | n.a. | n a | 15 |

PRELIMINARY RESULTS

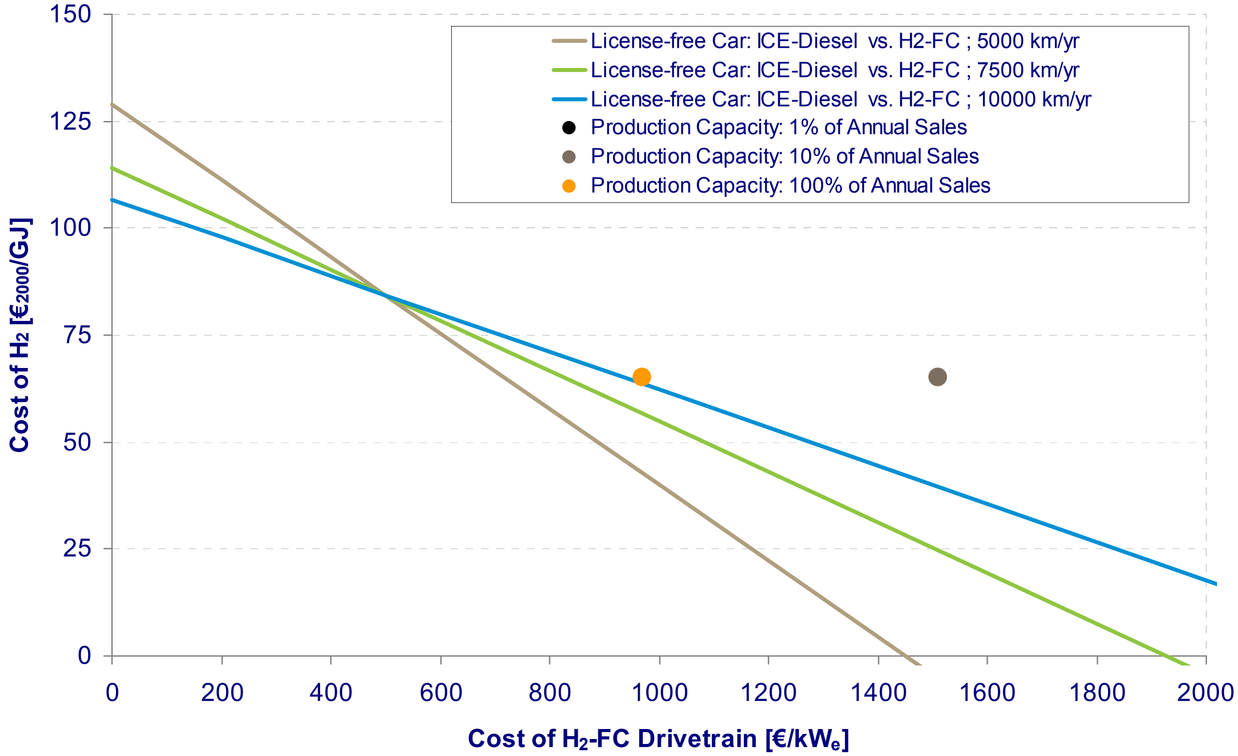
# „Windows of Economy“
## - Input parameters reference technology -

| Field of Application (Engine/Fuel) | Number of Units in total | Market Size in units sold per year | Engine Investment cost | Maintenance cost |
|---|---|---|---|---|
| | | | €/kW | €/unit |
| Passenger Car (SOTA ICE-Diesel) | 231 000 000 | 15 040 000 | 45,6 | 0,03 €/km |
| Passenger Car (SOTA ICE-Gasoline) | | | 35,0 | 0,02 €/km |
| Passenger Car (2020 ICE-Diesel) | | | 52,5 | 0,03 €/km |
| Passenger Car (2020 ICE-Gasoline) | | | 51,9 | 0,02 €/km |
| Bus (SOTA ICE-Diesel) | 600 000 | 40 000 | 45,6 | 0,07 €/km |
| Bus (SOTA Diesel Hybrid) | | | 66,0 | 0,09 €/km |
| Bus (2020 ICE-Diesel) | 600 000 | 40 000 | 52,5 | 0,07 €/km |
| Bus (2020 Diesel Hybrid) | | | 63,1 | 0,09 €/km |
| Light Truck (SOTA ICE-Diesel) | 30 000 000 | 2 000 000 | 45,6 | 0,07 €/km |
| Light Truck (SOTA Diesel Hybrid) | | | 66,0 | 0,09 €/km |
| Light Truck (2020 ICE-Diesel) | 30 000 000 | 2 000 000 | 52,5 | 0,07 €/km |
| Light Truck (2020 Diesel Hybrid) | | | 63,1 | 0,09 €/km |
| Licence-free Vehicle | 525 000 | 35 000 | 500 | 0,07 €/km |
| Outdoor Utility Vehicle (ICE-Diesel) | 300 000 | 20 000 | 500 | 0,07 €/km |
| Outdoor Utility Vehicle (Electric) | | | 2250 | |
| Scooter (ICE-Gasoline) | 14 000 000 | 1 400 000 | 70 | 0,02 €/km |
| Scooter (Electric) | | | 400 | 0,01 €/km |
| Forklift (ICE-Diesel) | 1 620 000 | 164 000 | 80 | 0,12 €/km |
| Forklift (ICE-LPG) | | | 85 | |
| Forklift (Electric 8/5) | 2 430 000 | | 600 | 0,7 €/km |
| Forklift (Electric 24/5) | | | 1000 | |
| Aircraft Tow Truck (ICE-Diesel) | 1250 | 80 | 100 - 200 | 0,71 - 2,14 €/hr |
| Aircraft Tow Truck (Electric) | | | 190,7 | |
| Sightseeing Boat (ICE-Diesel) | 500 | 30 | 257 | 1,79 - 2,56 €/hr |
| Sightseeing Boat (Electric) | | | 1500 | 1,64 - 1,74 €/hr |
| Truck APU (ICE-Diesel) | 100 000 | | | 0,08 €/hr |
| Pleasure Boat APU (ICE-Diesel) | 50 000 | | 500 | 0,50 €/hr |
| Mega-Yacht APU (ICE-Diesel) | 50 | | 400 | 2,44 €/hr |
| Back-up Telecom (Electric) | 417 000 | | 1837 | 476 €/yr |
| Back-up Hospitals (ICE-Diesel) | 14 900 | | 278 | 475 €/yr |
| Industrial CHP (Natural Gas) | 440 000 | | 633 | 0,0055 €/kWh |
| Residential CHP (Boiler) | 90 000 000 | | n.a. | |

# „Windows of Economy“ - Input parameters FC/$H_2$ technology-

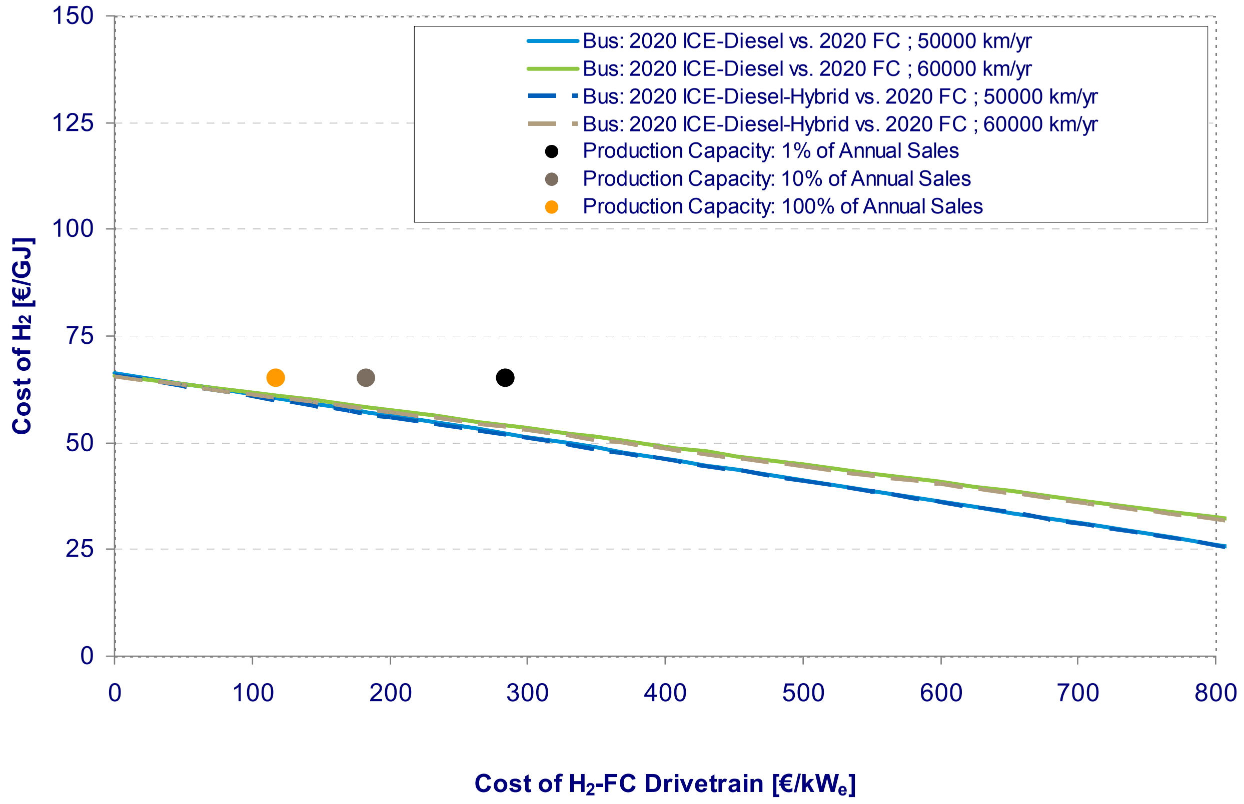
| (Field) of Application | FC/H2 Technology | Power FC/H2 Technology | $H_2$ use or fuel | Maintenance cost |
|---|---|---|---|---|
| | | kW | MJ/unit | €/unit |
| Passenger Car | PEMFC | 80 | 0,84 MJ/km | 0,01 €/km |
| | H2-ICE | 80 | 1,68 MJ/km | 0,02 €/km |
| Bus | PEMFC | 220 | 5,86 MJ/km | 0,02 €/km |
| | H2-ICE | 220 | 12,2 MJ/km | 0,04 €/km |
| Light Truck | PEMFC | 95 | 1 MJ/km | 0,02 €/km |
| Licence-free Vehicle | PEMFC | 4 | 0,6 MJ/km | 0,04 - 0,05 €/km |
| Outdoor Utility Vehicle | PEMFC | 4 | 0,6 MJ/km | 0,06 €/km |
| Scooter | PEMFC | 5 | 0,4 MJ/km | 0,01 €/km |
| Forklift | PEMFC | 20 - 45 | 4 - 7 MJ/km | 0,05 - 0,06 €/km |
| Aircraft Towing Vehicle | PEMFC | 75 | 18,5 MJ/hr | 0,71 - 1,43 €/hr |
| Sightseeing Boat | PEMFC | 16 | 30 MJ/hr | 1,03 - 1,74 €/hr |
| Truck APU | PEMFC | 5 | 10 MJ/km | 0,04 €/hr |
| Pleasure Boat APU | DMFC | 0,063 | Methanol | |
| Mega-Yacht APU | reforming + PEMFC | 500 | Methanol | 2,00 €/hr |
| Back-up Telecom | PEMFC | 1,100 | 9 MJ/kWh | 476 €/yr |
| Back-up Hospitals | PEMFC | 200 | 7,2 MJ/kWh | 475 €/yr |
| Industrial CHP | reforming + PEMFC | 200 | Natural Gas | 0,0055 €/kWh |
| | MCFC | | | |
| | SOFC + GT | | | |
| Residential CHP | SOFC | 1 | Natural Gas | 250 €/kWh |

# SOTA FC License-free Cars
## - Attractive with high mileage -




- Windows of Opportunity for license-free cars based on SOTA reference technologies, prices and policies
- The data points reflect SOTA $H_2$-FC specifications assuming equal lifetime of the stack and application
- Attractive, if annual mileage is high, which can be questioned

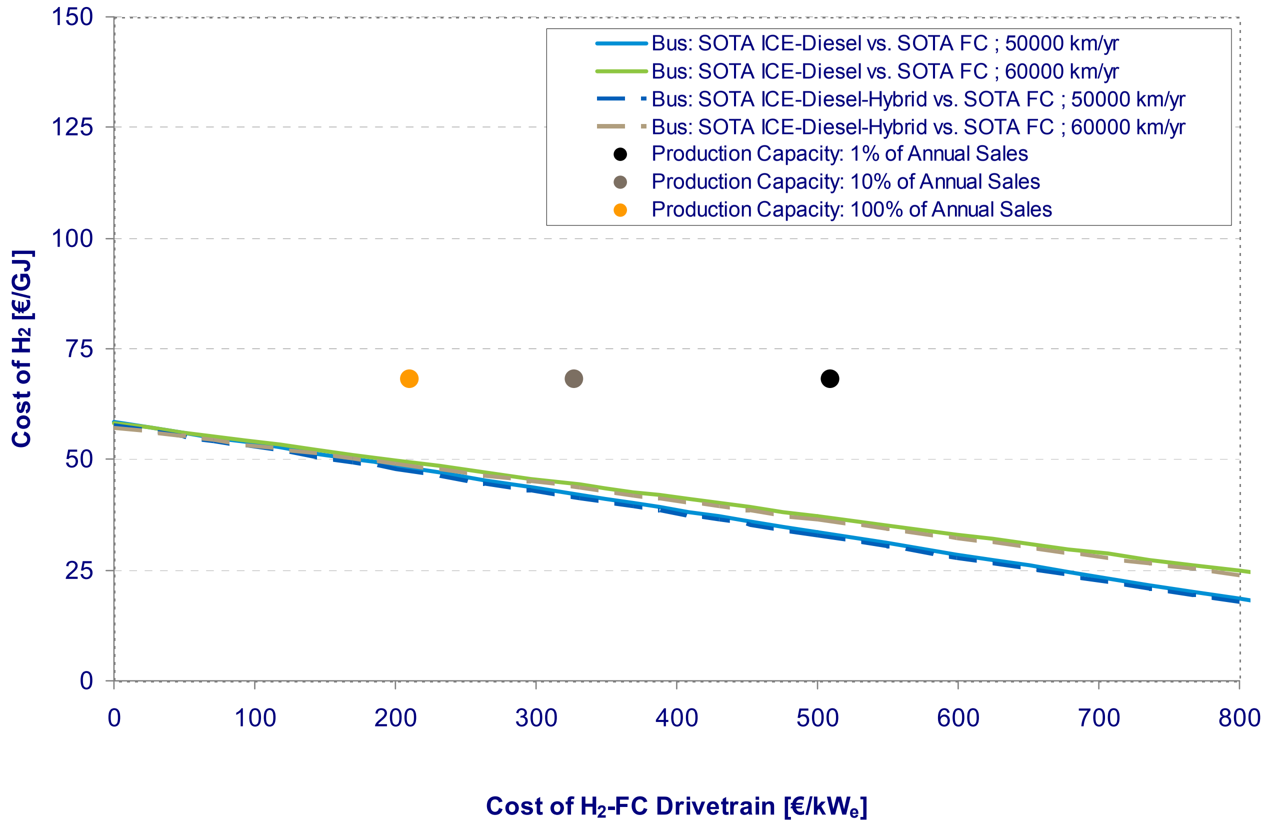
# 2020 FC Buses
# - Economically Difficult -




- Windows of Opportunity for buses based on 2020 reference technologies, prices and policies (without $CO_2$ tax)
- The data points reflect 2020 $H_2$-FC specifications assuming equal lifetime of the stack and application
- 2020 $H_2$-FC difficult case for buses in terms of economics due to high fuel consumption (price of hydrogen is limiting)
- **BUT:** Improvement of local air quality and synergies in the development of refuelling infrastructure

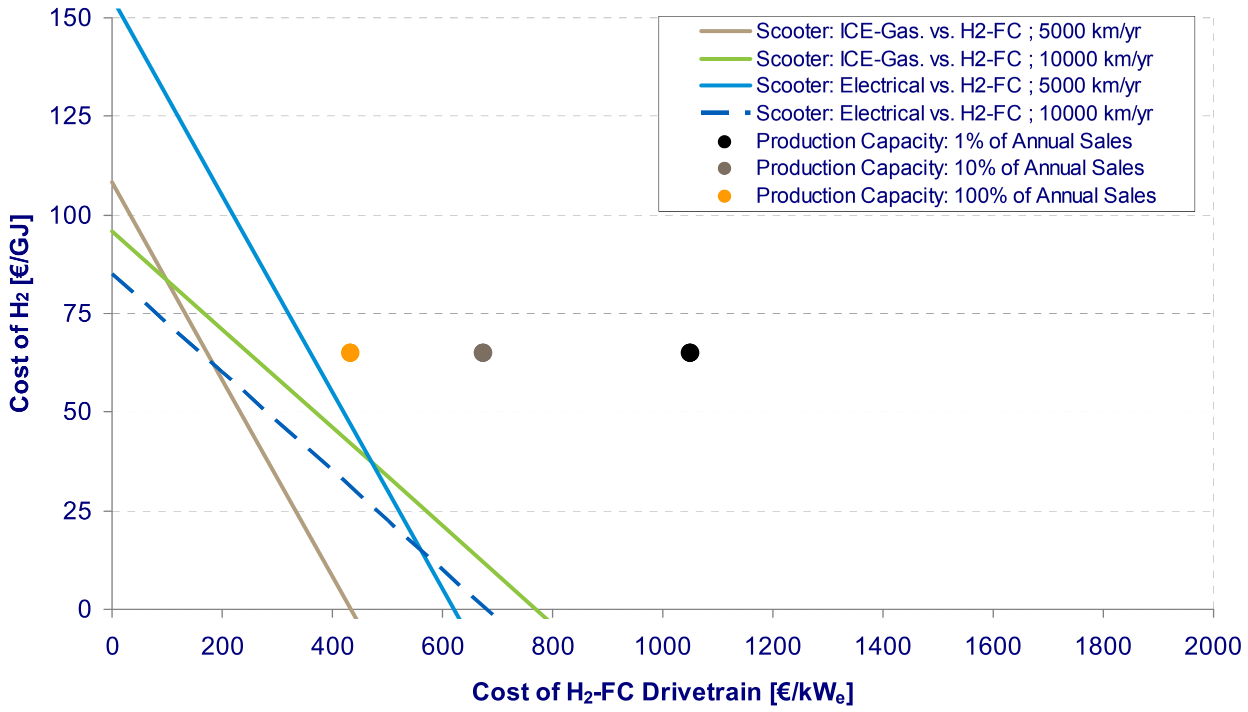
PRELIMINARY RESULTS

# SOTA FC Buses
## - Economically Difficult -




- Windows of Opportunity for buses based on SOTA reference technologies, prices and policies
- The data points reflect SOTA $H_2$-FC specifications assuming equal lifetime of the stack and application
- SOTA $H_2$-FC difficult case for buses in terms of economics due to high fuel consumption (price of hydrogen is limiting)

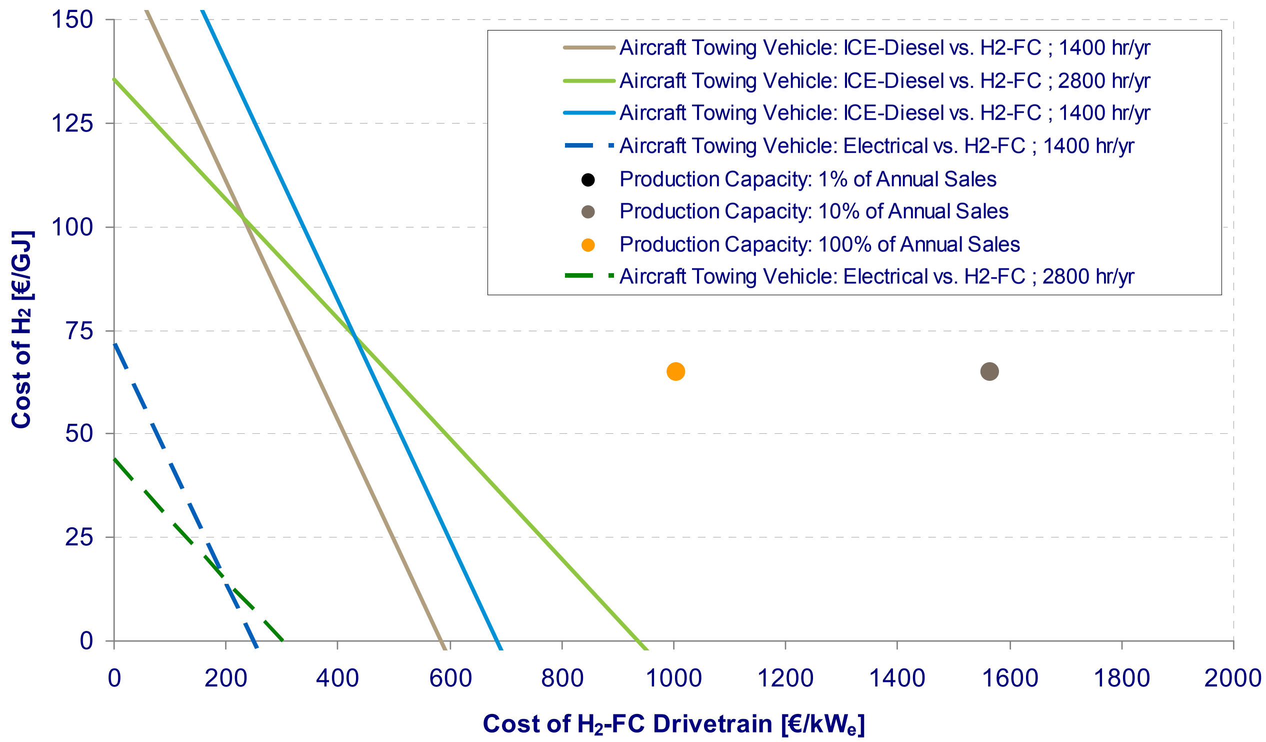
# SOTA FC Scooter - Economically Difficult -




- Windows of Opportunity for Scooter based on SOTA reference technologies, prices and policies
- The data points reflect SOTA $H_2$-FC specifications assuming equal lifetime of the stack and application
- Not very sensitive towards price of hydrogen
- High cost of FC drivetrain due to small system power

- Market Size: 1,4 million sold vehicles per year; thus the contribution to economy of scale effects would be significant

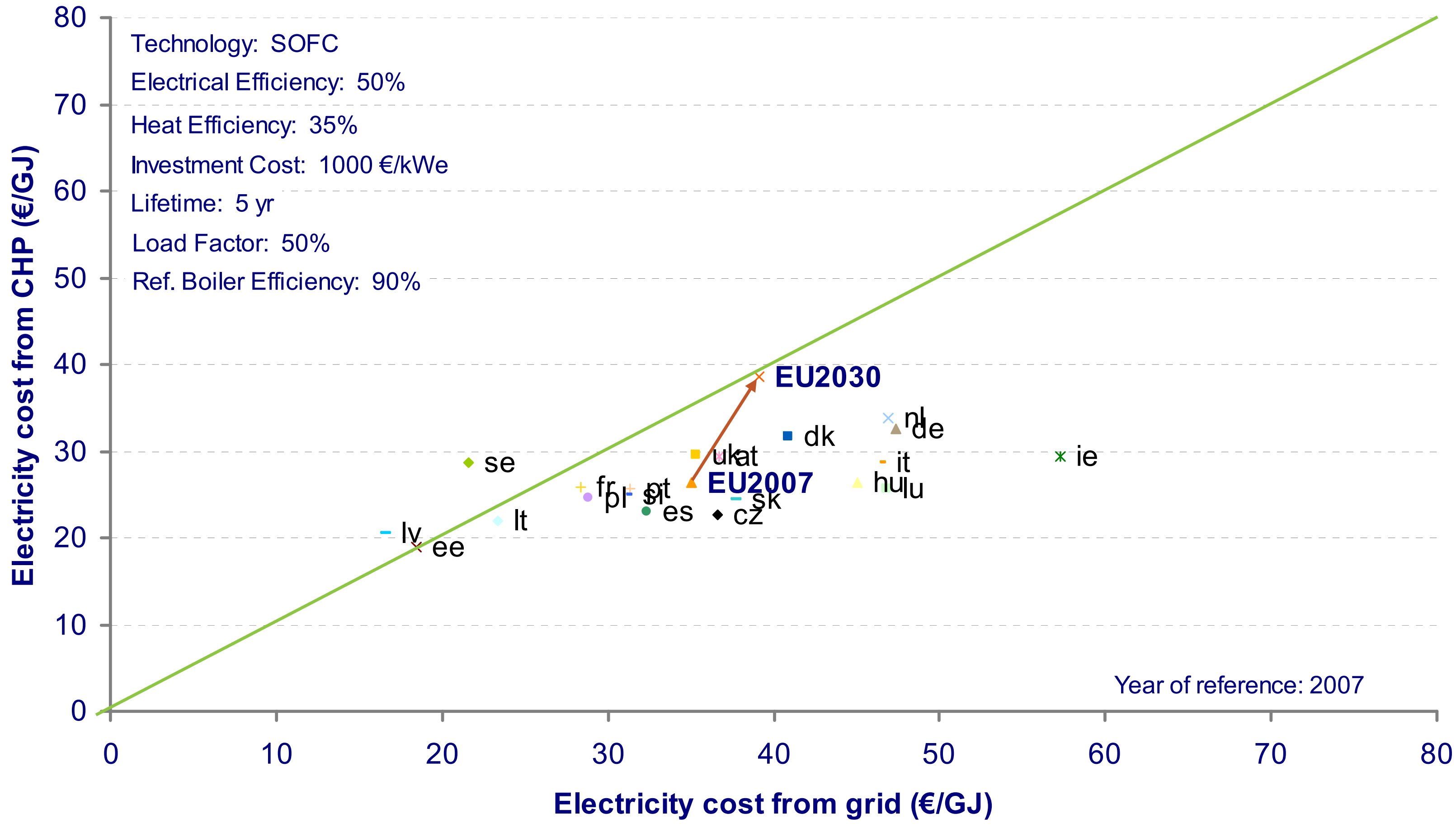
# SOTA Aircraft Tow Trucks - Economically Difficult -




- Windows of Opportunity for Aircraft Tow Trucks based on SOTA reference technologies, prices and policies
- The data points reflect SOTA $H_2$-FC specifications assuming equal lifetime of the stack and application
- Economics are difficult due to small market size

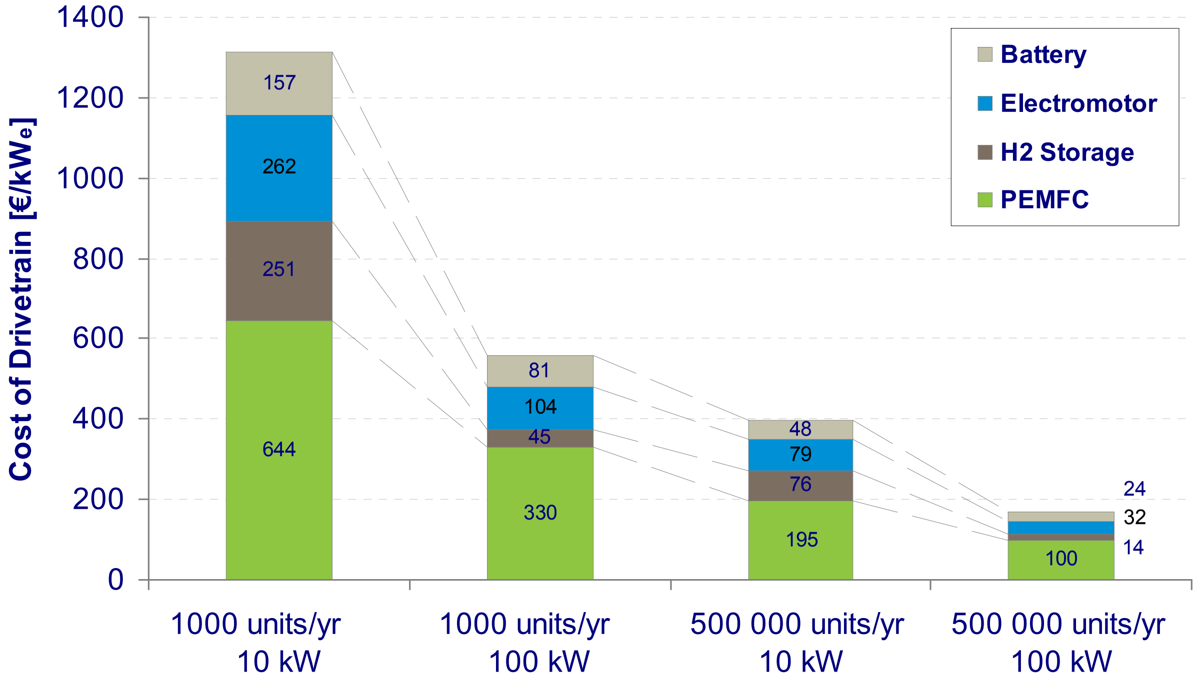
PRELIMINARY RESULTS

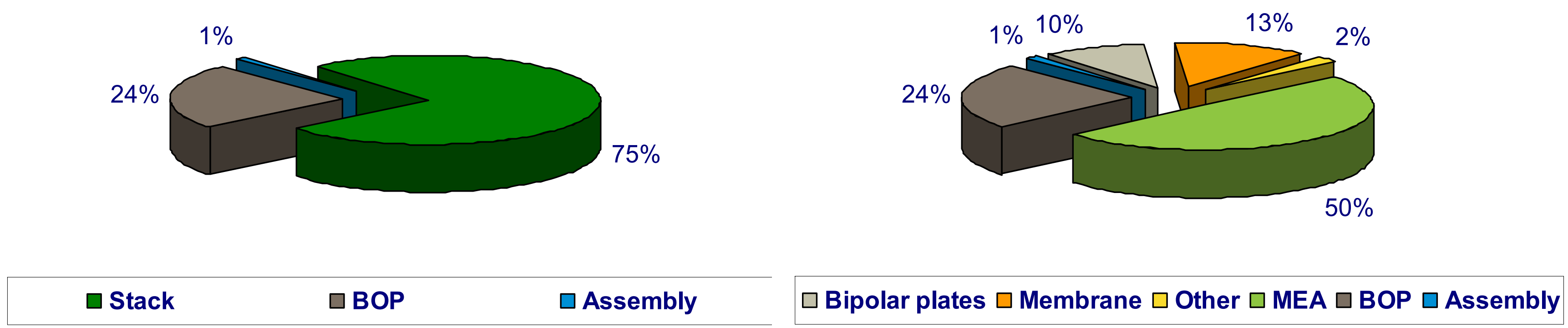
# Economics for Industrial CHP Application - SOFC -



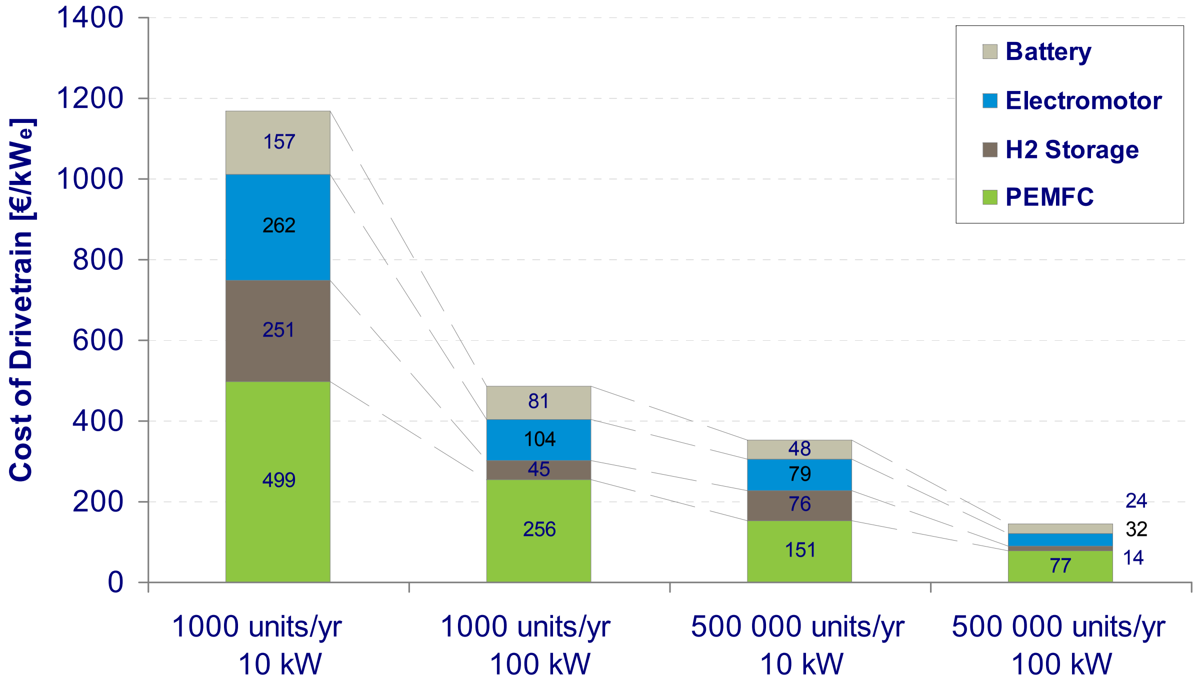

PRELIMINARY RESULTS

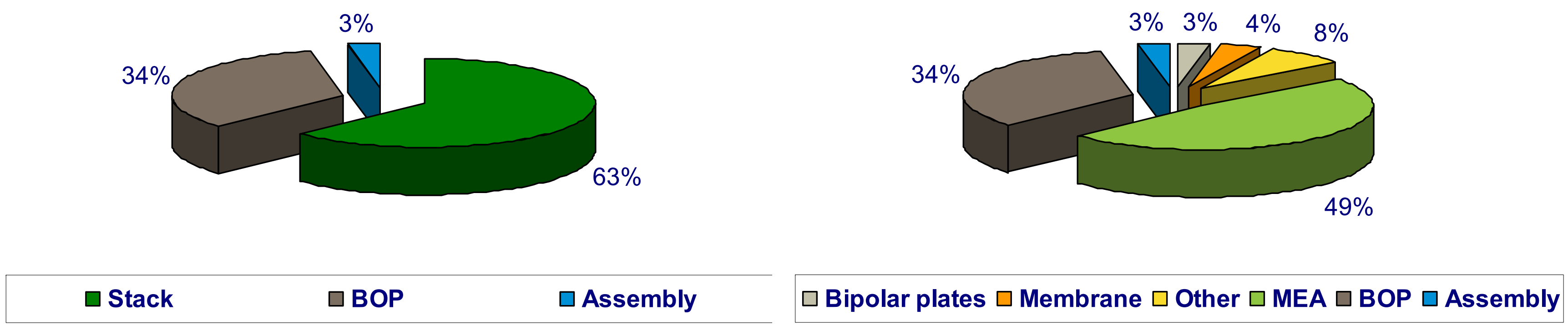
# Cost Breakdown of FC Drivetrain
## - Pt price: 2000 $/troz -



# Cost Breakdown of FC Drivetrain
## - Pt price: 900 $/troz -



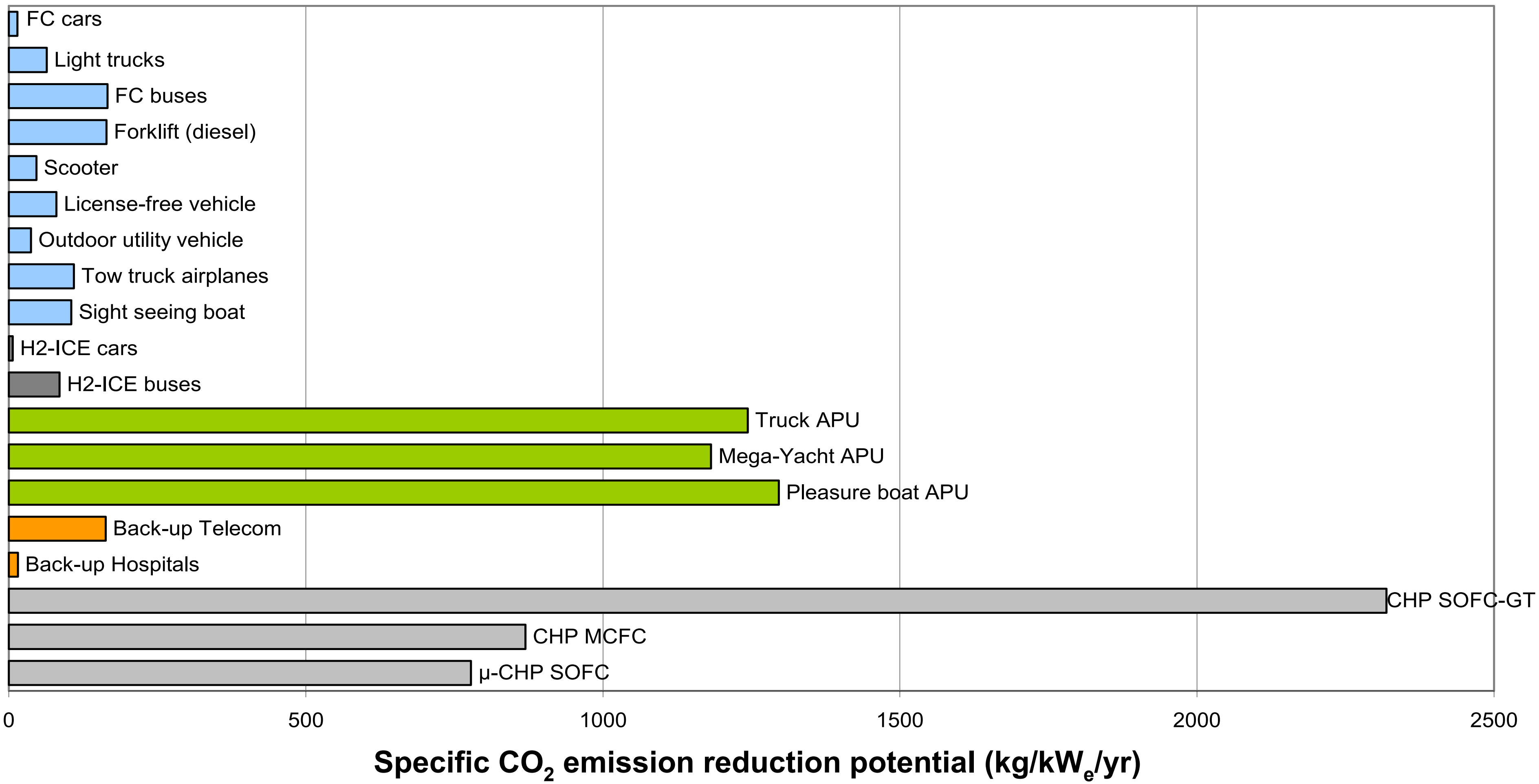

**PRELIMINARY RESULTS**

# Requirements of Cost Reductions for FC Drivetrains

- **The results indicate that research is essential to reduce the costs of fuel cell systems for nearly every application to become cost competitive to conventional technologies by:**
  - Increase durability of fuel cell system
  - Increase power density of fuel cell
  - Less use of Platinum or cheaper materials

# Stationary applications and auxiliary power units (APU) have the most important specific emission reduction potential for an installed power...

## Specific $CO_2$ emission reduction potential




- HyWays hydrogen mix

**PRELIMINARY RESULTS**