Energy &Transport

Prospects for hydrogen and fuel cell vehicles

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- Introduction
- Historical developments
- Characteristics of hydrogen
- The hydrogen vision
- Hydrogen supply chain
- Economic and environmental assessment
- Hydrogen as a storage
- Conclusion

Introduction

Basic principle:

$$S=f(E, \eta\ (Tc), \eta\ (Tis))$$

Service: km driven

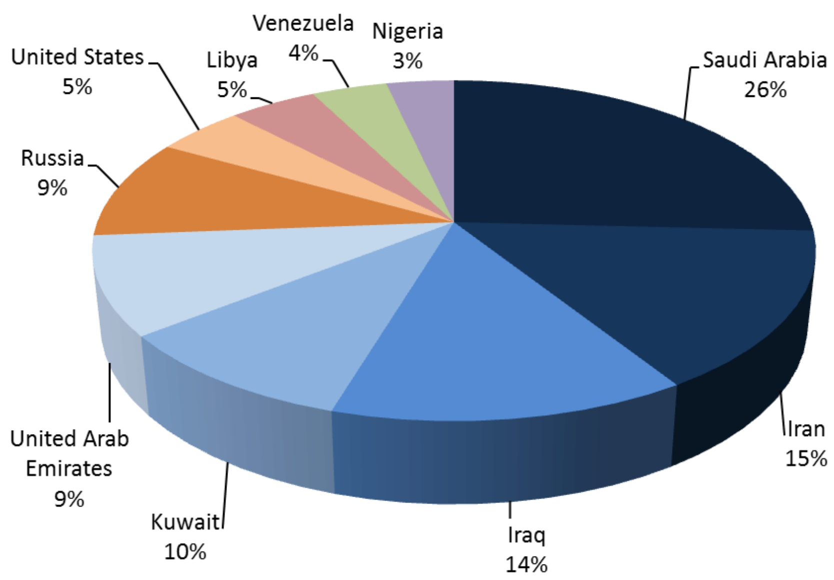
Fuel mix, Fuel demand

Efficiency: Liter/100 km

Infrastructur

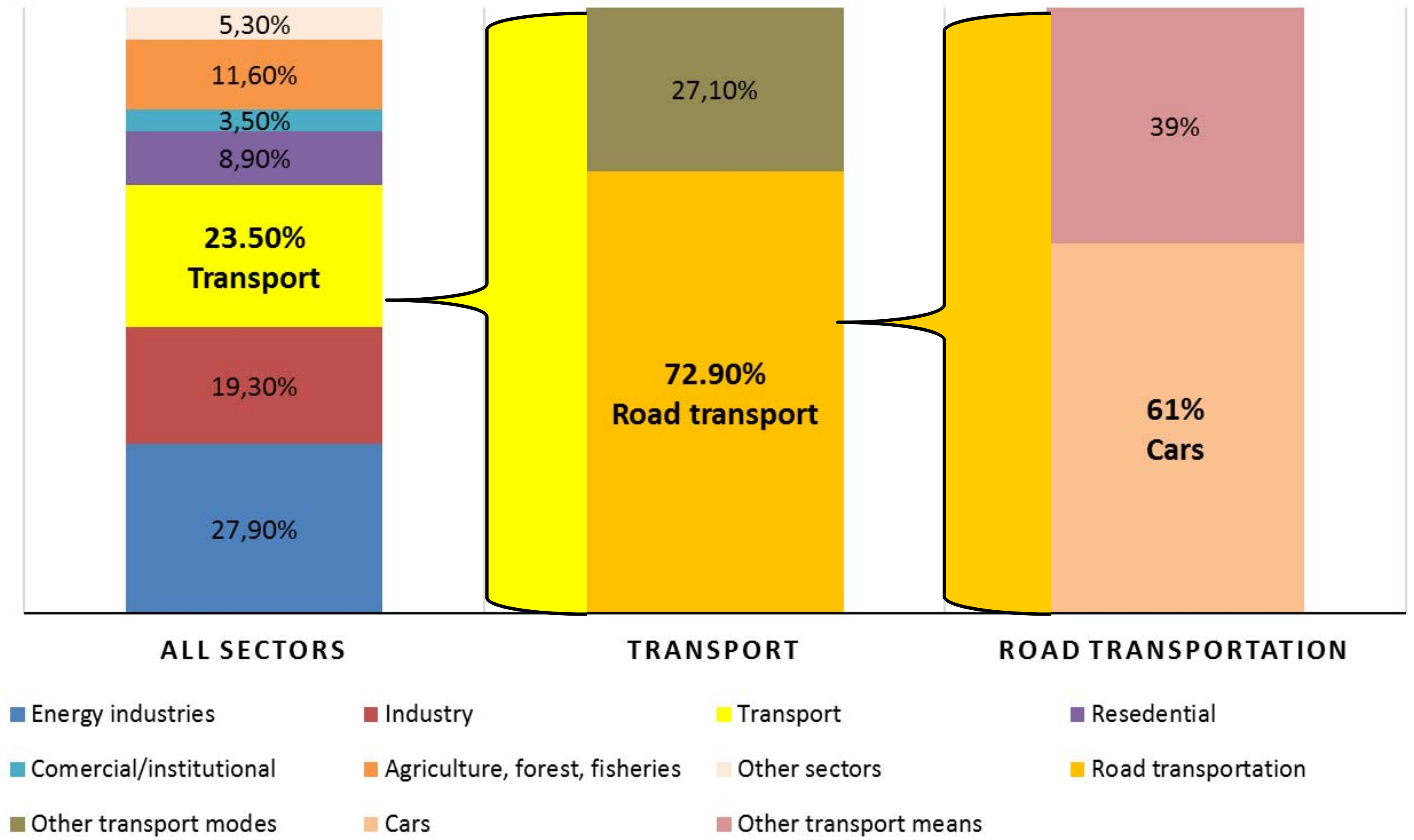
Transport sector

- oil products
- least-diversified
- energy import dependency

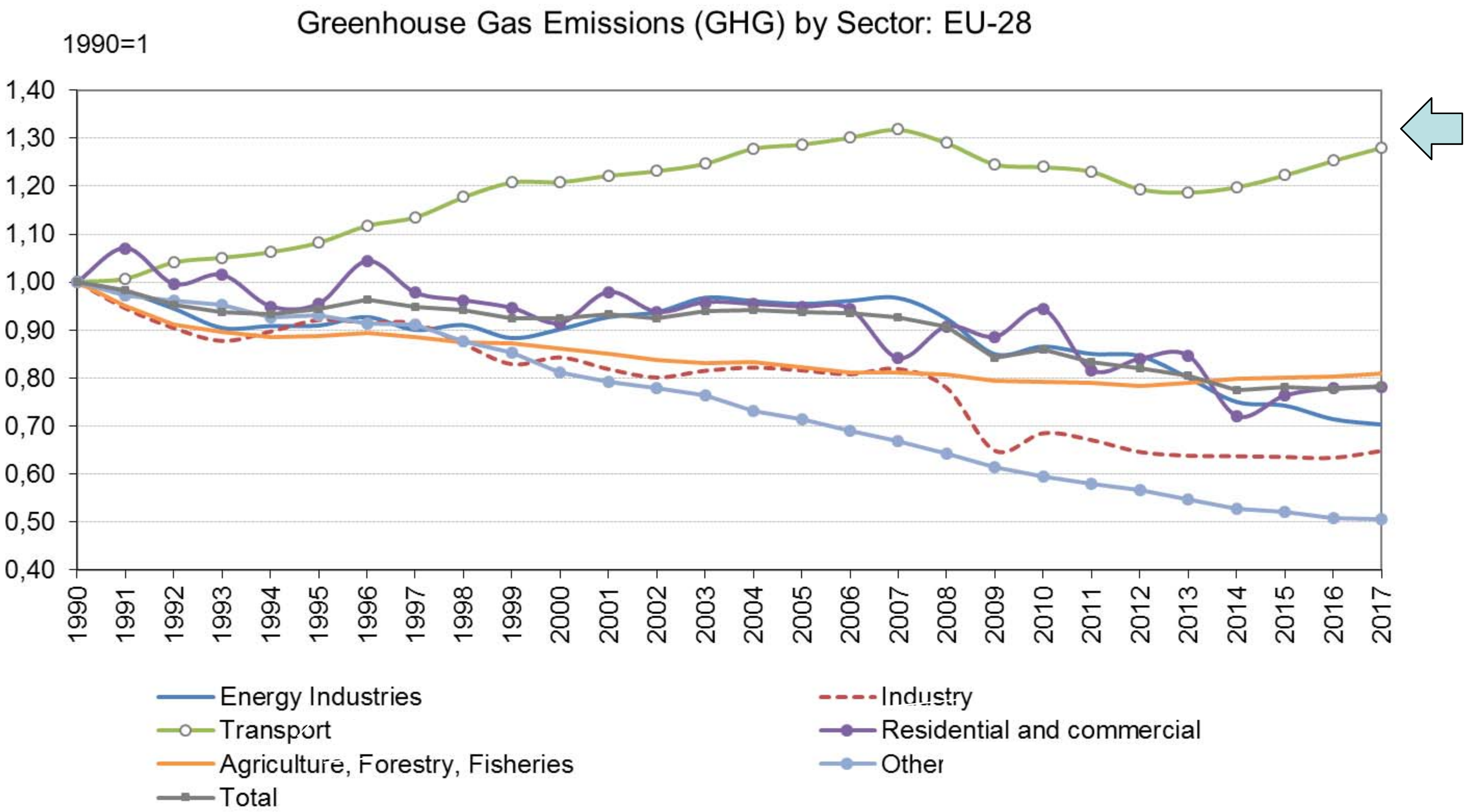


Countries with largest conventional oil reserves

GHG emissions in EU 28



GHG


Greenhouse Gas Emissions (GHG) by Sector: EU-28
1990=1
1,40
1,30
1,20
1,10
1,00
0,90
0,80
0,70
0,60
0,50
0,40
1990
1991
1992
1993
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1999
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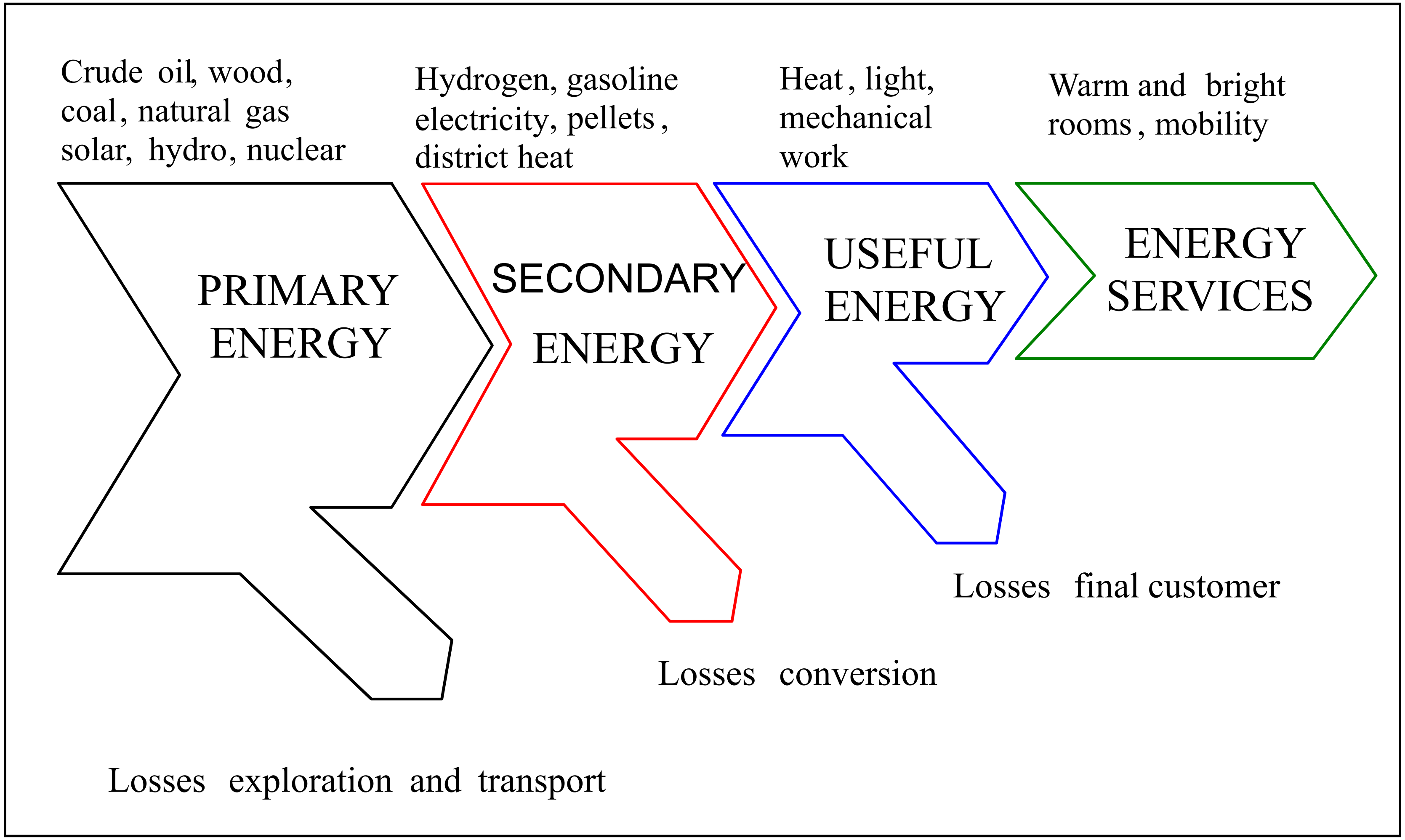
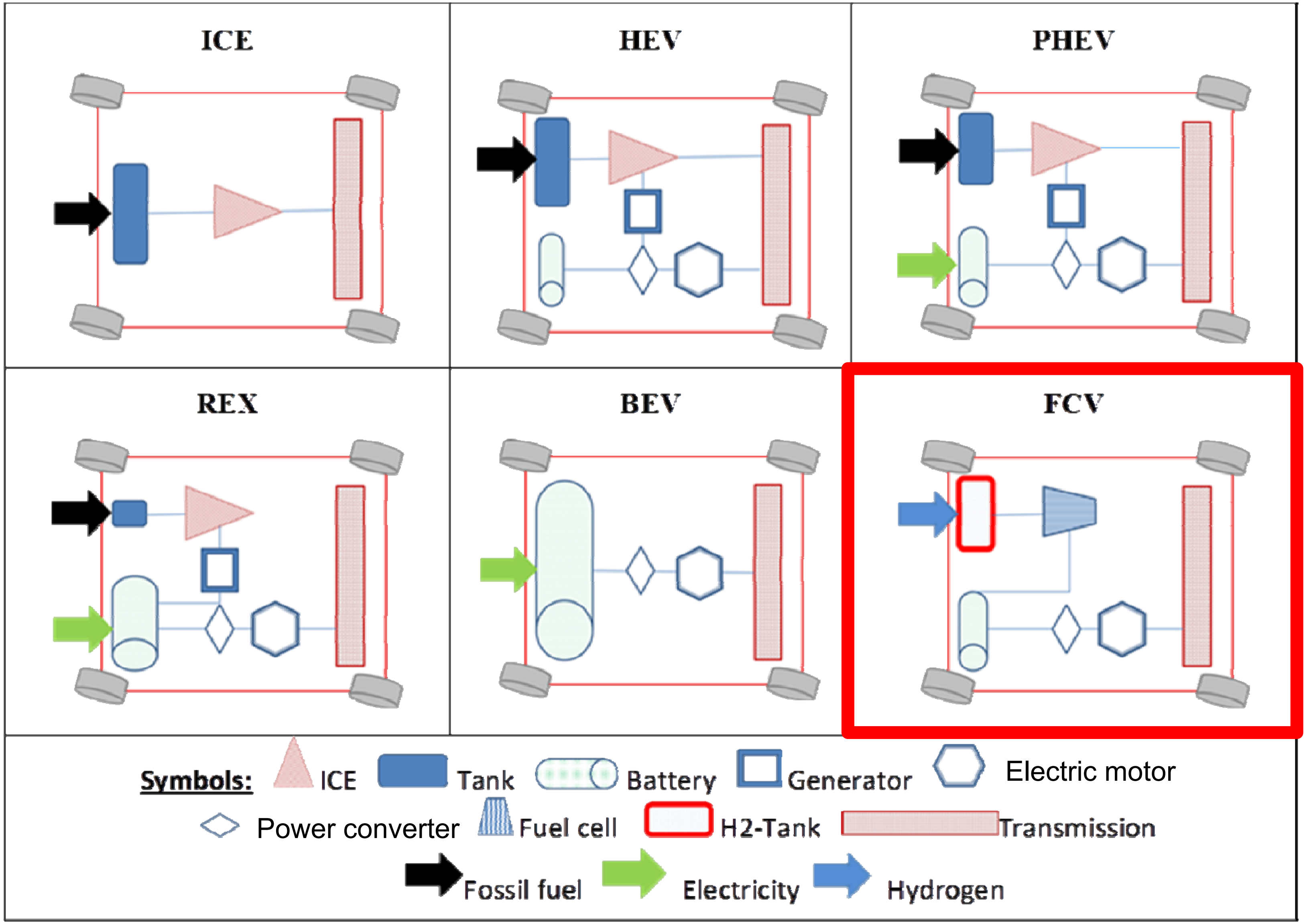
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Energy Industries
Industry
Transport
Residential and commercial
Agriculture, Forestry, Fisheries
Other
Total

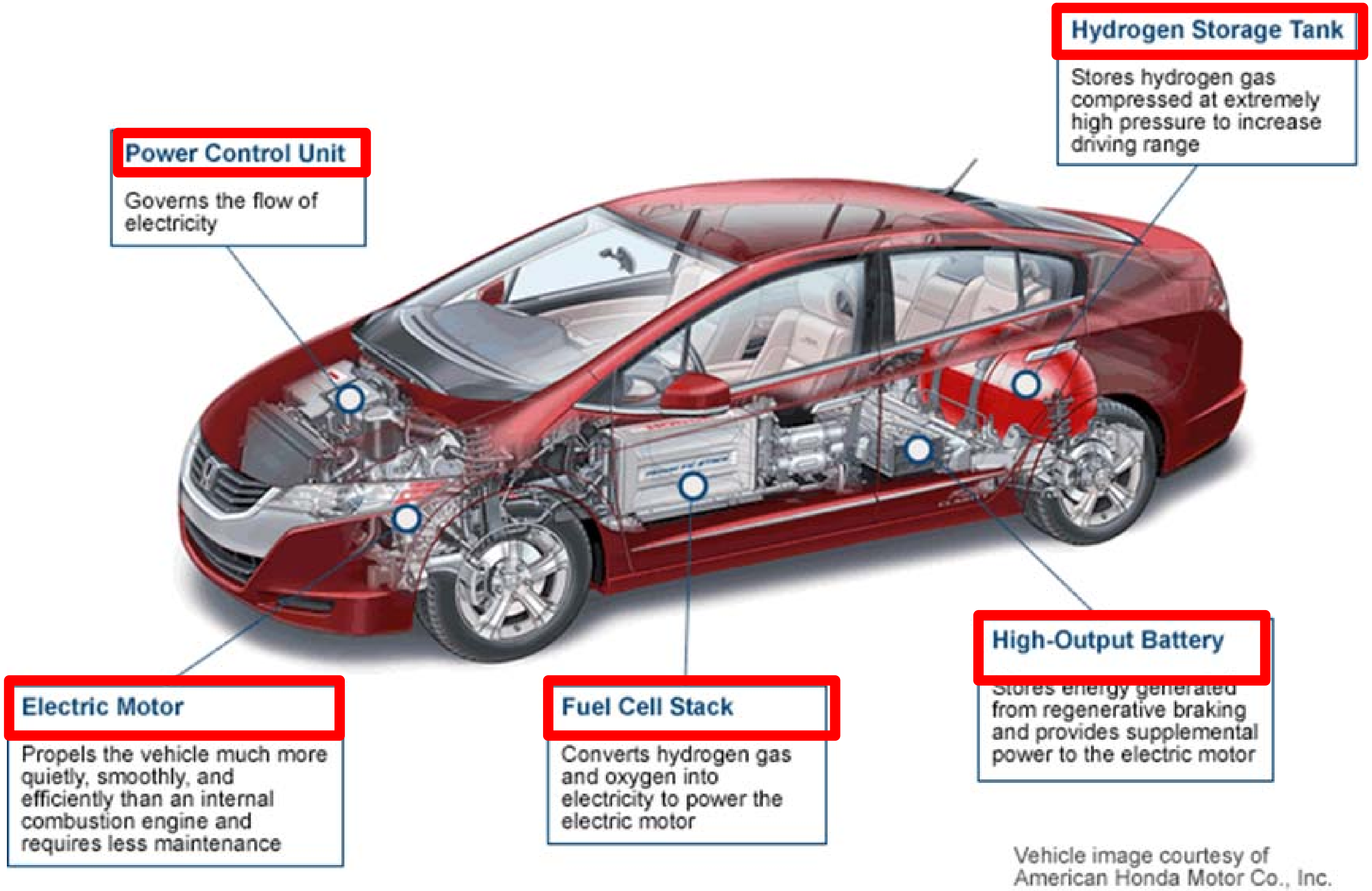
Energy supply chains



Electric vehicles

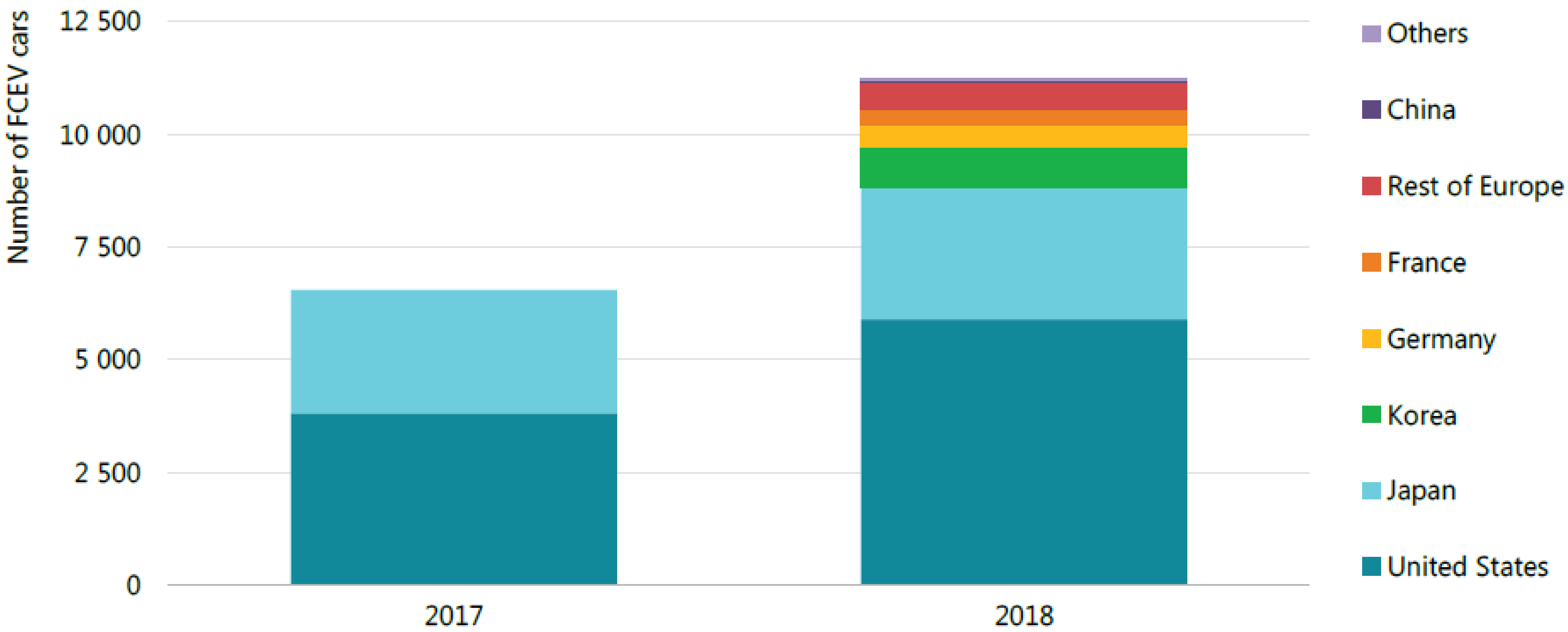


FCV



Major components of a fuel cell-powered passenger car

Fuel cell electric cars

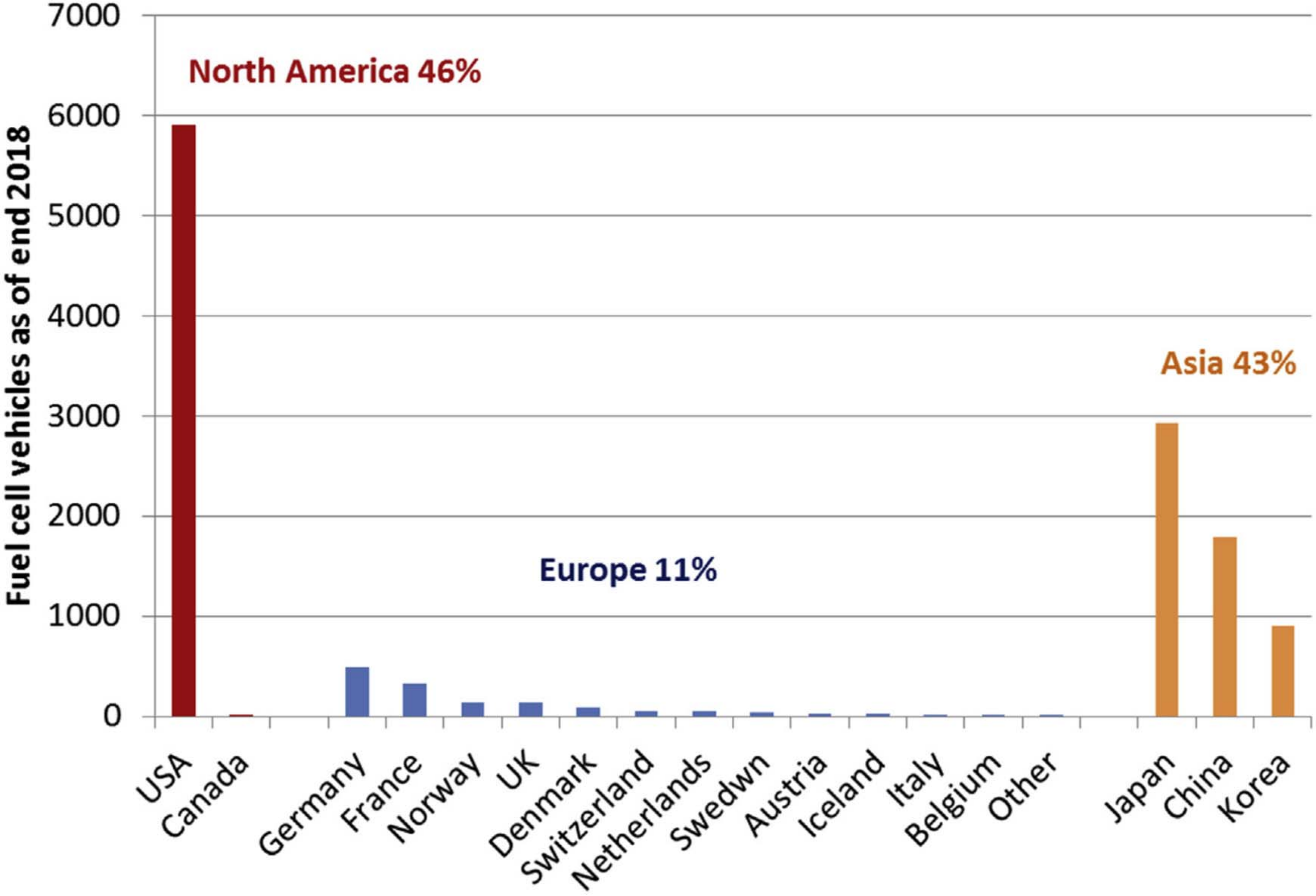


Source: AFC TCP (2019), *AFC TCP Survey on the Number of Fuel Cell Electric Vehicles, Hydrogen Refuelling Stations and Targets*.

About 4 000 fuel cell electric cars were sold in 2018, growth of almost 56% over the previous year, but this still represents a small fraction of the global light-duty vehicle fleet.

IEA, 2019

Fuel cell electric cars



FCVs

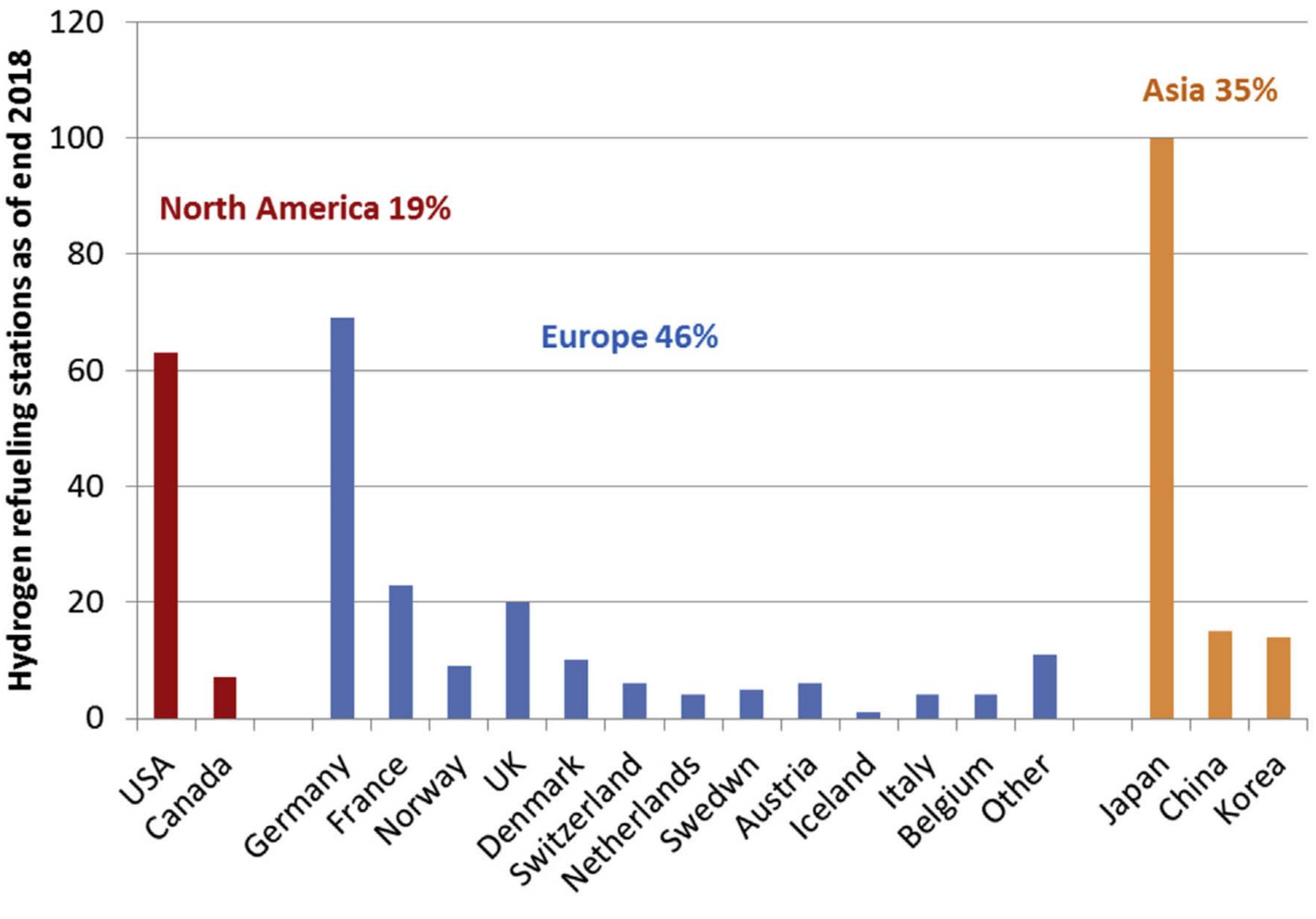
The main reasons for the slow introduction of FCVs:

- Costs

Application	Power or energy capacity	Energy efficiency	Investment cost	Lifetime	Maturity
Fuel cell vehicles	80 - 120 kW	Tank-to-wheel efficiency 43-60%	USD 60 000-100 000	150 000 km	Early market introduction

- Consumer acceptance
- Infrastructure

Hydrogen refuelling stations and utilisation, 2018



Some history of hydrogen

Some history

1766 Hydrogen was first identified as a distinct element by British scientist Henry Cavendish

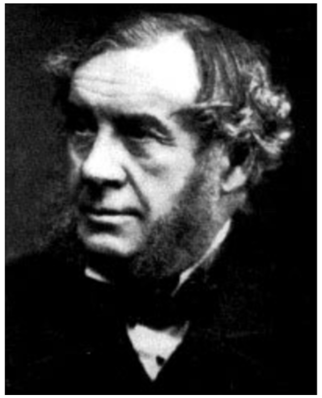
1788 French chemist Antoine Lavoisier gave hydrogen its name, which was derived from the Greek words—"hydro" and "genes," meaning "water" and "born of."

1800 English scientists William Nicholson and Sir Anthony Carlisle discovered that applying electric current to water produced hydrogen and oxygen gases. This process was later termed "electrolysis."

1807 Isaac de Rivas makes a hydrogen gas powered vehicle - first with internal combustion power - however, very unsuccessful design

Some history

1838 The fuel cell effect, combining hydrogen and oxygen gases to produce water and an electric current, was discovered by Swiss chemist Christian Friedrich Schoenbein.



The vision of the hydrogen economy is very old. Still, in 1874 Jules Verne in his work "The Mysterious Island" said:

"*I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable*."

Some history

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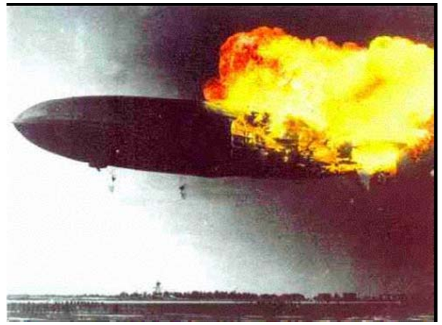


1889 Ludwig Mond and Charles Langer attempted to build the first fuel cell device using air and industrial coal gas. They named the device a fuel cell.

1920 British scientist, J.B.S. Haldane, introduced the concept of renewable hydrogen in his paper Science and the Future by proposing that “there will be great power stations where during windy weather the surplus power will be used for the electrolytic composition of water into oxygen and hydrogen.”

1937 After successful trans-Atlantic flights from Germany to the United States, the Hindenburg, a dirigible inflated with hydrogen gas, crashed upon landing in Lakewood, New Jersey. The mystery of the crash was solved in 1997. A study concluded that the explosion was not due to the hydrogen gas.

Some history

1958 The United States formed the National Aeronautics and Space Administration (NASA). NASA's space program currently uses the most liquid hydrogen worldwide, primarily for rocket propulsion and as a fuel for fuel cells.

2004 The world's first fuel cell-powered submarine undergoes deepwater trials (Germany navy).

2005 Twenty-three states in the U.S. have hydrogen initiatives in place.

Today-2050 Future Vision:

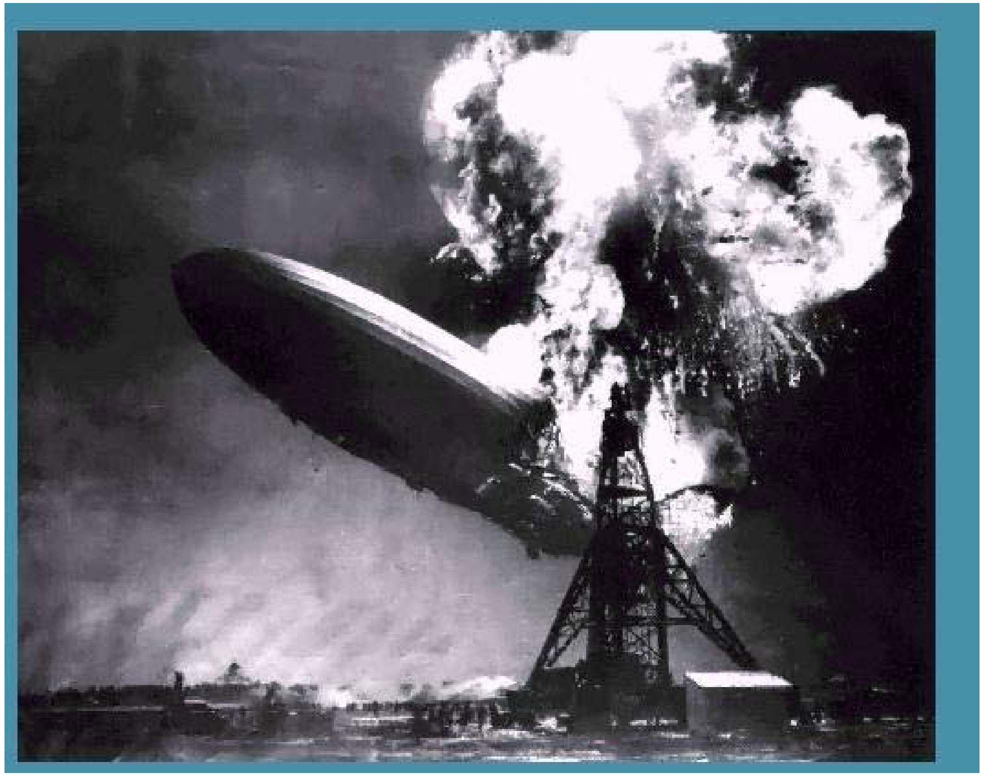
In the future, water will replace fossil fuels as the primary resource for hydrogen. Hydrogen will be distributed via national networks of hydrogen transport pipelines and fueling stations. Hydrogen energy and fuel cell power will be clean, abundant, reliable, affordable and an integral part of all sectors of the economy in all regions of the U.S.

Some characteristics of hydrogen

Hydrogen

- Hydrogen is the simplest, lightest and most abundant element in the universe
- Secondary energy carrier …. It can be produced from different energy sources
- Hydrogen is less flammable than gasoline
- Hydrogen is non-toxic
- Hydrogen combustion produces only water
- Storage for surplus electricity

How safe is hydrogen ?



•The explosion of the airship Hindenburg at Lakehurst, NJ, on May 6, 1937, serves as one of the most spectacular moments recorded by the media. But, the main cause of the disaster was pilot error. The only way to prevent the disaster would have been if the pilot had chosen to land in better conditions elsewhere, which was very feasible, considering he had had enough fuel remaining to reach all the way to California.

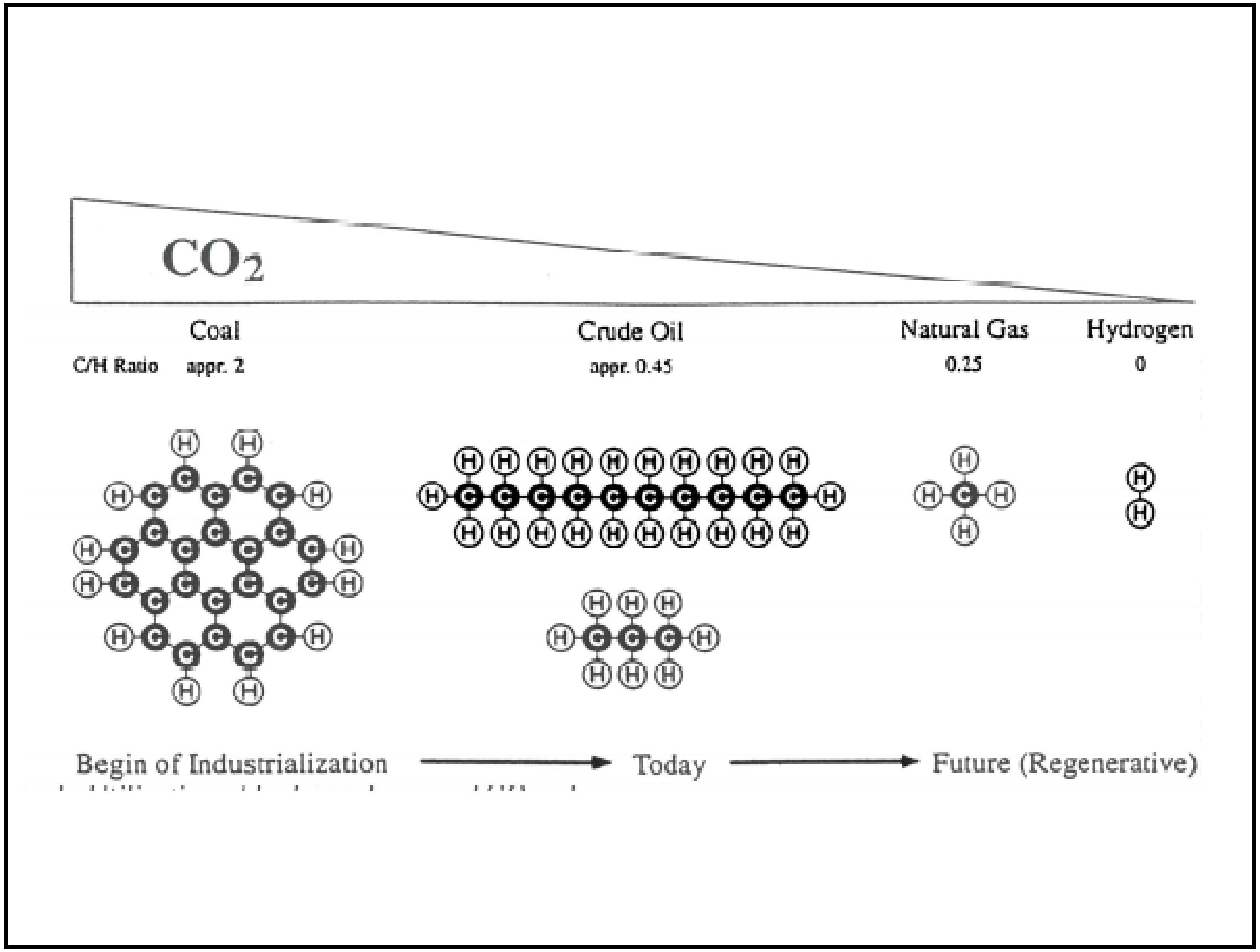
How safe is hydrogen ?

- No fuel we currently use or have yet to develop will be totally without hazards, through all the processes of production, transportation, and consumption, just as no kitchen knife can be used without risk.

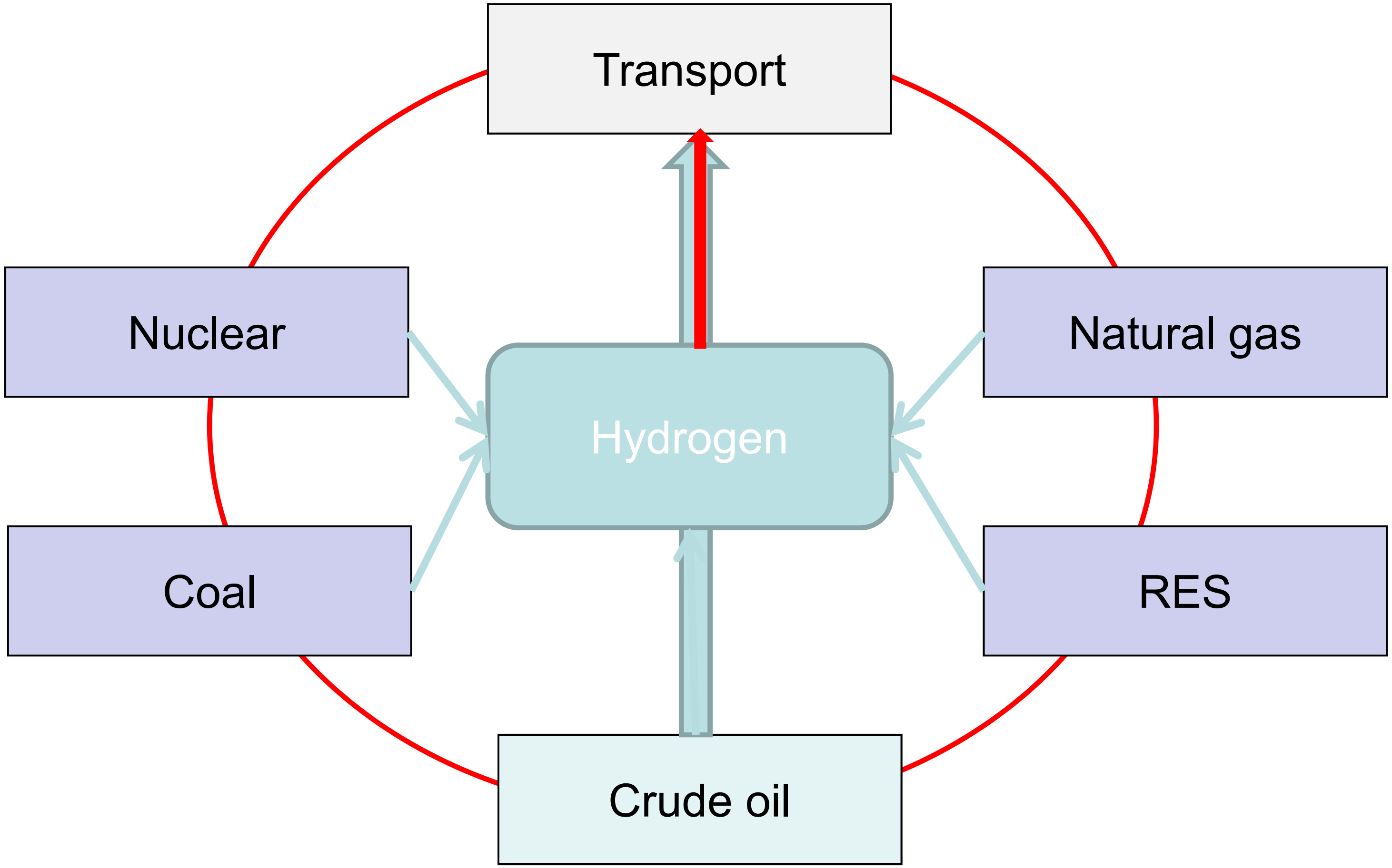
  We must recognize that each of us has learned to use knives safely, and do so daily. As long as we use wisdom in our methods of production, storage, and use of hydrogen, we'll enjoy the same safety we have had with petroleum fuels, with the additional benefit of fewer health hazards when leaks do occur.

Quelle: www.hydrogennow.org

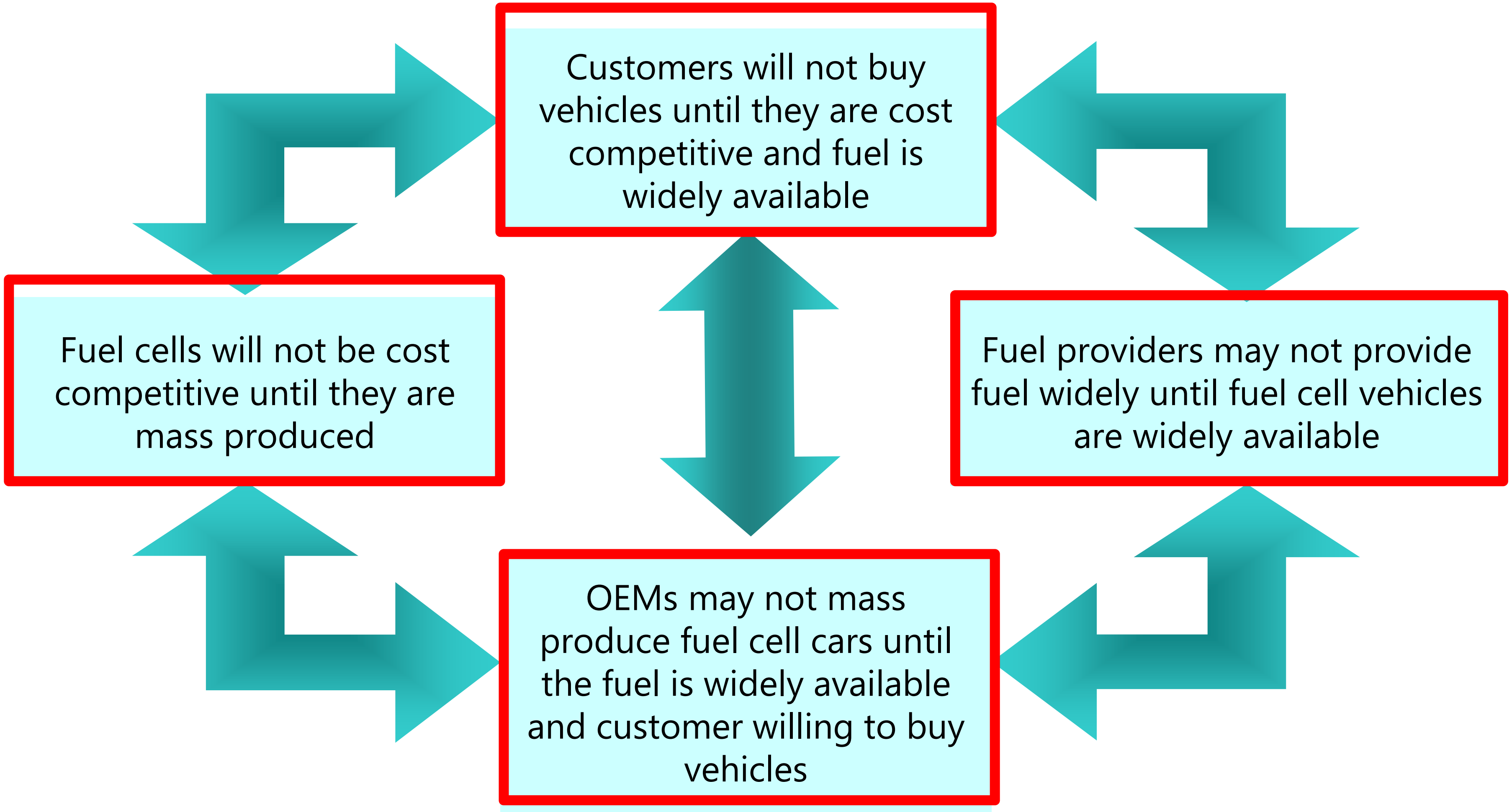
Decarbonisation



Diversification



’Chicken and egg’ dilemma

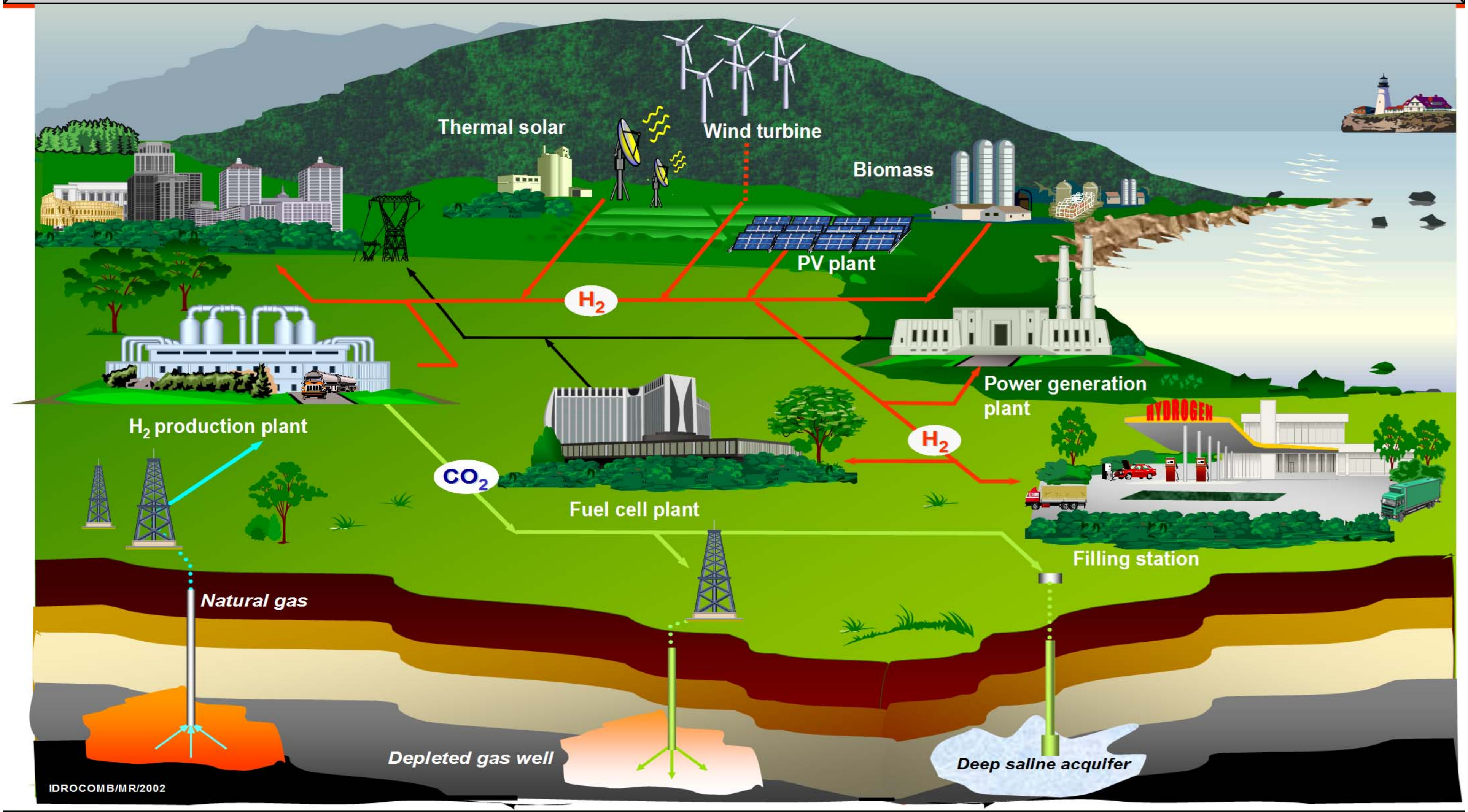


The transition to a hydrogen economy is complex

OEM-Original Equipment Manufacturer

The hydrogen vision

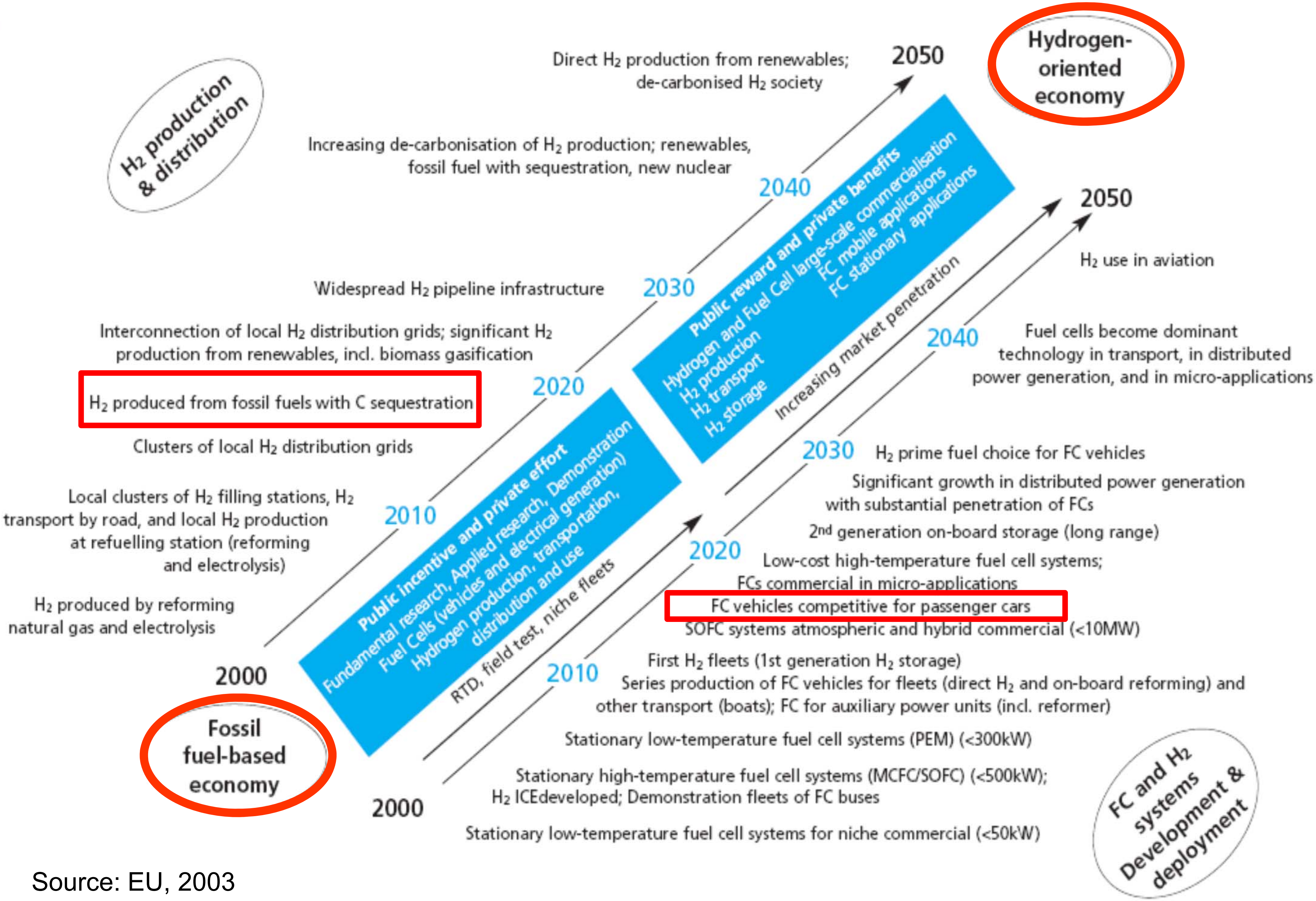
The hydrogen vision



This is how an integrated energy system of the future might look – combining large and small fuel cells for domestic and decentralised heat and electrical power generation. Local hydrogen networks could also be used to fuel conventional or fuel cell vehicles.

Source: EU, 2003

A challenging European hydrogen vision



Source: EU, 2003

Uses of hydrogen

	Current role	Demand perspective
Cars and vans (light-duty vehicles)	11 200 vehicles in operation, mostly in California, Europe and Japan	The global car stock is expected to continue to grow; hydrogen could capture a part of this market

Toyota Mirai

Honda Clarity

Hyundai Tucson

Hyundai Genesis

Uses of hydrogen

	Current role	Demand perspective
Trucks and buses **(heavy duty vehicles)**	Demonstration and niche markets: ~25 000 forklifts ~500 buses ~400 trucks ~100 vans. Several thousand buses and trucks expected in China* by end-2019	Strong growth segment; long-haul and heavy-duty applications are attractive for hydrogen

Hydrogen Bus in the UK

Sunline Transit H2 Bus in CA

Hydrogen Bus in Norway

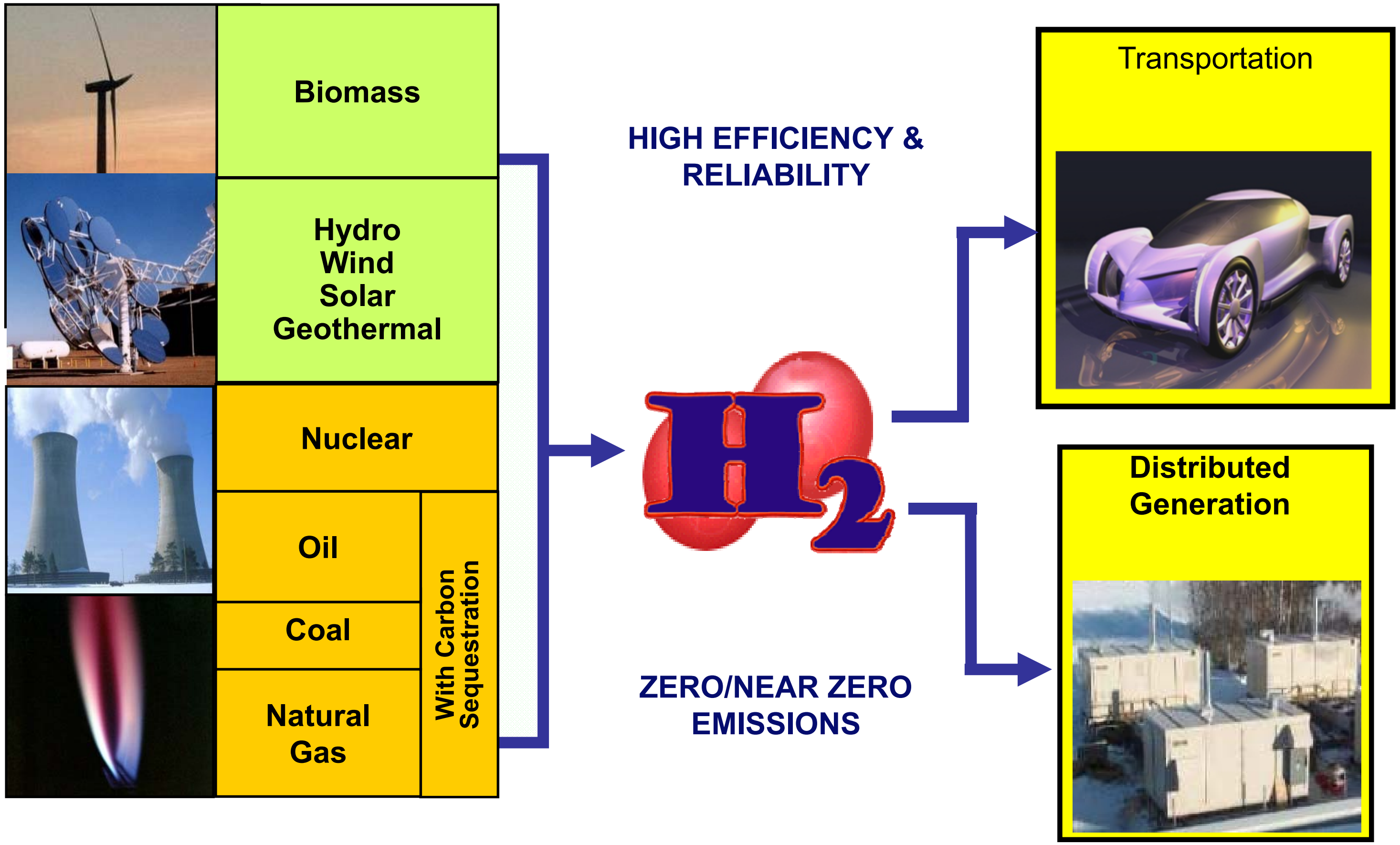
Uses of hydrogen

	Current role	Demand perspective
Rail	Two hydrogen trains in Germany	Rail is a mainstay of transport in many countries

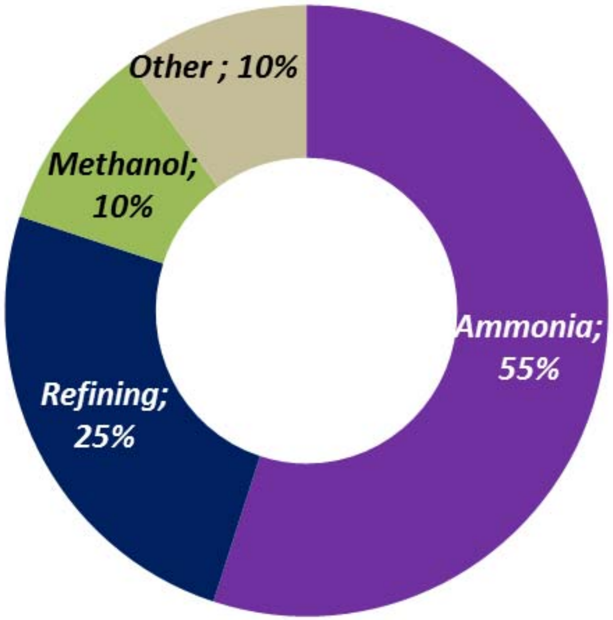
Coradia iLint Train, Germany

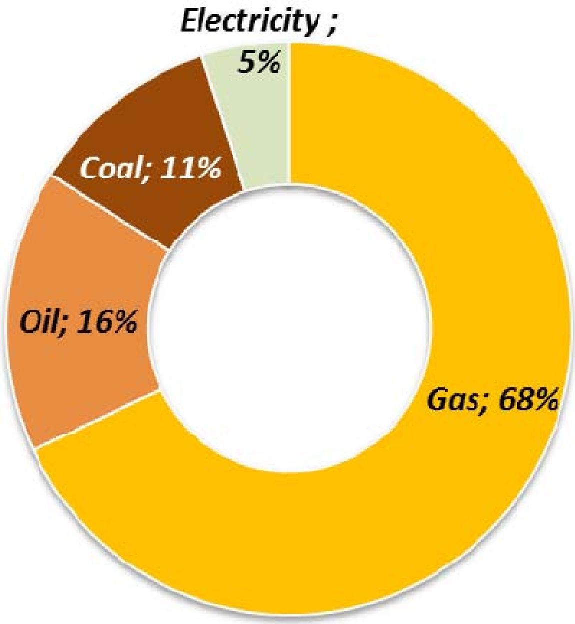
The hydrogen supply chains

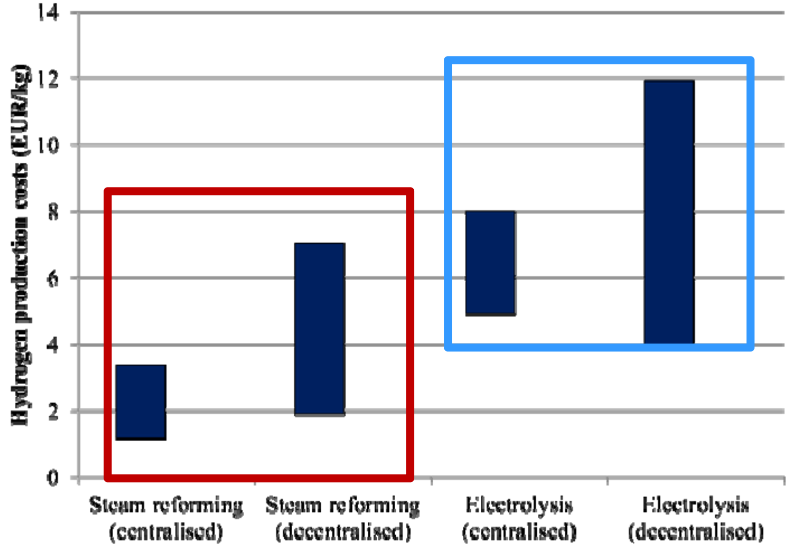
Hydrogen supply chains



Global hydrogen use and production







Major hydrogen production processes

Primary Method	***Process***	***Feedstock***	***Energy***	***Emissions***	***Stage of Development***
	Steam Reforming	*Natural Gas*	*High temperature steam*	*Some emissions. Carbos sequestration can mitigate their effect.*	*Developed commercial technology*
	Thermochemical Water Splitting	*Water*	*High temperature heat from advanced gas-cooled nuclear reactors*	*No emissions*	*Fundamental research*
Thermal	*Gasification*	*Coal*, Biomass***	*Steam and oxygen at high temperature and pressure*	*Some emissions. Carbos sequestration can mitigate their effect.*	**Developed commercial technology **Proven technology*
	Pyrolysis	*Biomass*	*Moderately high temperature steam*	*Some emissions. Carbos sequestration can mitigate their effect.*	*Proven technology*

Major hydrogen production processes

Primary Method	*Process*	*Feedstock*	*Energy*	*Emissions*	*Stage of Development*
	Electrolysis	*Water*	*Electricity from wind, solar,hydro and nuclear*	*No emissions.*	*Developed commercial technology*
Electrochemical	*Electrolysis*	*Water*	*Electricity from coal or natural gas*	*Some emissions from electricity production.*	*Developed commercial technology*
	Photo-Electro-chemical	*Water*	*Direct sunlight*	*No emissions.*	*Fundamental research*

Major hydrogen production processes

Primary Method	**Process**	**Feedstock**	**Energy**	**Emissions**	**Stage of Development**
	Photobiological	*Water and algae strains*	*Direct sunlight*	*No emissions.*	*Fundamental research*
Biological	*Anaerobic Digestion*	*Biomass*	*High temperature heat*	*Some emissions.*	*Fundamental research*
	Fermentative Microorganisms	*Biomass*	*High temperature heat*	*Some emissions.*	*Fundamental research*

Hydrogen production

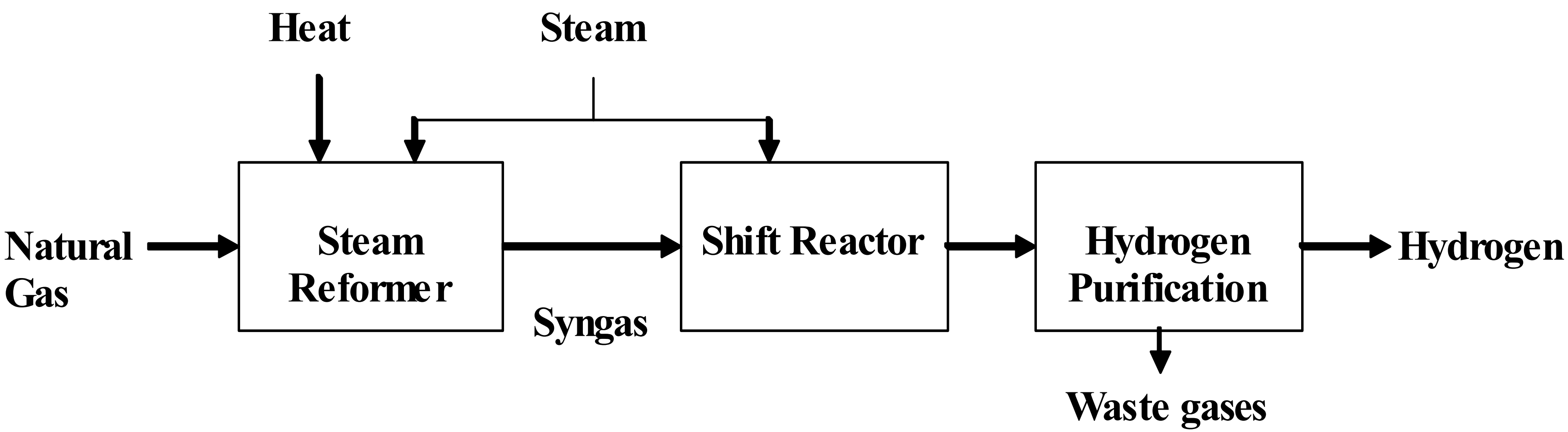
Hydrogen production:

- **Steam reforming**
- **Electrolysis**

Hydrogen production

Steam reforming of natural gas

- The steam reforming process involves supplying steam and natural gas to a catalytic bed at 800-850°C and pressures of 2.5 MPa to form hydrogen and carbon monoxide. This is followed by exothermic catalytic conversion (shift reaction) to convert carbon monoxide with more steam to carbon dioxide and hydrogen. The carbon dioxide is removed from the gas mixture using absorption or membrane separation to produce high purity hydrogen.



Hydrogen production

Steam reforming of natural gas

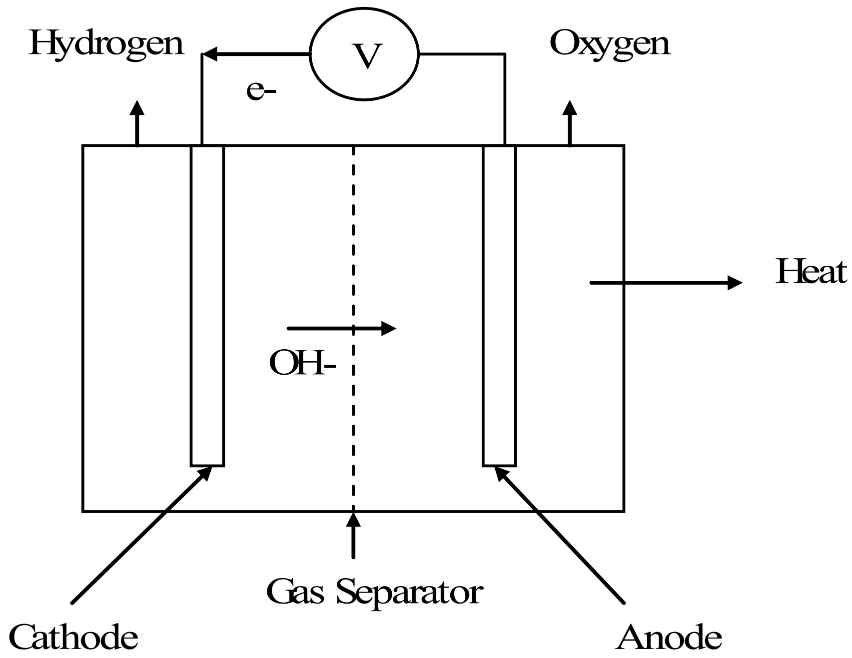
Application	*Power or capacity*	*Efficiency*	*Initial investment cost*	*Life time*	*Maturity*
Steam reformer, large scale	150-300 MW	70-85%	400-600 USD/kW	30 years	Mature
Steam reformer, small scale	0.15-15 MW	~51%	3 000-5 000 USD/kW	15 years	Demon-stration

In steam reforming of natural gas ca. **7 kg CO_2** are produced per kg hydrogen.

Hydrogen production

Electrolysis

- The use of electricity to split water into hydrogen and oxygen is called electrolysis. In principle electrolysis works by passing a direct current through two electrodes, the anode and cathode, put in water. Pure water is a very poor conductor of electricity, so an electrolyte like salt should be added to improve the conductivity of the water and to increase the efficiency of the process.



Electrolyzer

Application	***Power or capacity***	***Efficiency***	***Initial investment cost***	***Life time***	***Maturity***
Alkaline electrolyser	Up to 150 MW	63-70%	500-1 400 USD/kW	60 000- 90 000 hours	Mature
PEM electrolyser	Up to 150 kW (stacks)Up to 1 MW (systems)	56-60%	1 100-1 800 USD/kW	30 000- 90 000 hours	Early market

Electrolysis requires ca. **9 liters** of water to produce **1 kg** hydrogen.

IEA, 2019

Hydrogen transport

	Capacity	Transport distance	Energy loss	Fixed costs	Variable costs	Deployment phase
Gaseous tube trailers	Low	Low	Low	Low	High	Near term
Liquefied truck trailers	Medium	High	High	Medium	Medium	Medium to long term
Hydrogen pipelines	High	High	Low	High	Low	Medium to long term

Qualitative overview of hydrogen T&D technologies for hydrogen delivery in the transport sector

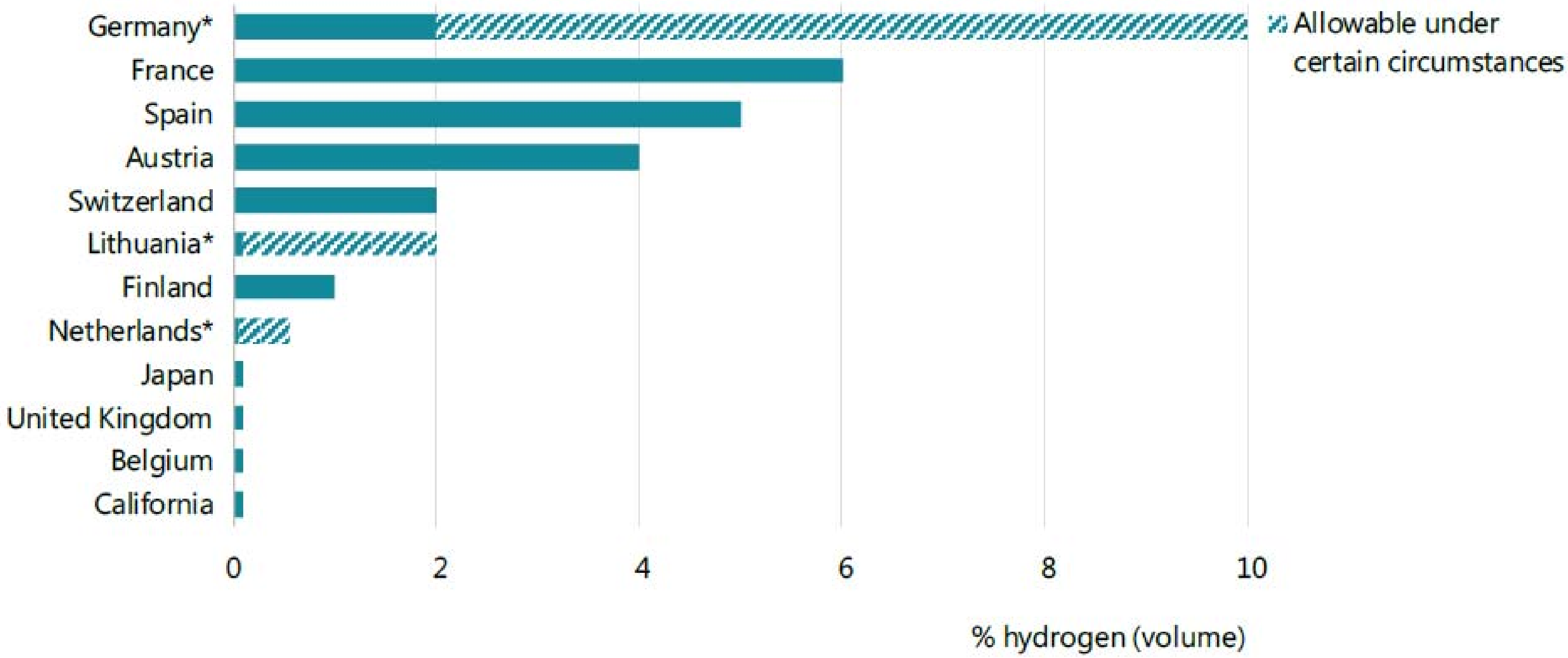
IEA, 2015

Hydrogen transport

Application	Power or energy capacity	Energy efficiency	Investment cost	Maturity
Tube trailer (gaseous) for hydrogen delivery	Up to 1 000 kg	~100% (without compression)	USD 1 000 000 (USD 1 000 per kg payload)	Mature
Liquid tankers for hydrogen delivery	Up to 4 000 kg	Boil-off stream: 0.3% loss per day	USD 750 000	Mature
Pipeline	-	95%, incl. compression	Rural: USD 300 000-1.2 million/ km Urban: USD 700 000-1.5 million / km (dependent on diameter)	Mature

IEA, 2015

Current limits on hydrogen blending in natural gas networks



* Higher limit for Germany applies if there are no CNG filling stations connected to the network; higher limit for the Netherlands applies to high-calorific gas; higher limit for Lithuania applies when pipeline pressure is greater than 16 bar pressure.

Today most countries limit hydrogen concentrations in the natural gas network; modifying these regulations will be necessary to stimulate meaningful levels of hydrogen blending.

Hydrogen transport

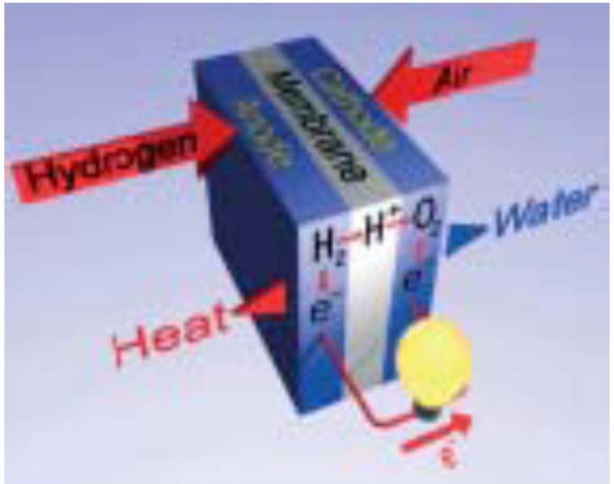
Hydrogen pipeline systems - Europe

Region	Length (km)	Pressure (MPa)
Belgium, France, NL	966	10
Germany: Rhine-Rhur	240	1.1/2.3/30
Germany: Leuna-Merseburg	100	2-2.5
UK	16	5
Sweden	18	0.5-2.8
Europe (in total)	**~ 1500**	

Linde,2004

Fuel cells

Fuel cells convert fuel and air directly to electricity, heat and water in an electrochemical process.



Their advantages are:

- high efficiency
- zero emissions
- mechanical simplicity, low vibration and noise, low maintenance requirements

Types of fuel cells

Application	Power or capacity	Efficiency	Initial investment cost	Life time	Maturity
Alkaline FC	Up to 250 kW	~50%	USD 200-700/kW	5 000-8 000 hours	Early market
PEMFC stationary	0.5-400 kW	32%-49%	USD 3 000-4 000/kW	~60 000 hours	Early market
PEMFC mobile	80-100 kW	Up to 60%	USD ~500/kW	<5 000 hours	Early market
SOFC	Up to 200 kW	50%-70%	USD 3 000-4 000/kW	Up to 90 000 hours	Demon-stration
PAFC	Up to 11 MW	30%-40%	USD 4 000-5 000/kW	30 000-60 000 hours	Mature
MCFC	KW to several MW	More than 60%	USD 4 000-6 000/kW	20 000-30 000 hours	Early market

Benefits of transport fuel cells

• **Efficiency:**

Fuel cell cars have demonstrated high efficiencies

• **Regulated emissions**:

Fuel cell cars have very low emissions, and even zero emissions at the point of use

• **Power:**

Fuel cells can provide on-board electricity with high efficiency. Fuel cell cars could produce (back-up) power for homes, offices, or remote locations

Economic and ecological aspects

Economic assessment

The costs per km driven C_{km} are calculated as:

$$C_{km} = \frac{IC \cdot \alpha}{skm} + P_f \cdot FI + \frac{C_{O\&M}}{skm}$$

[€/100 km driven]

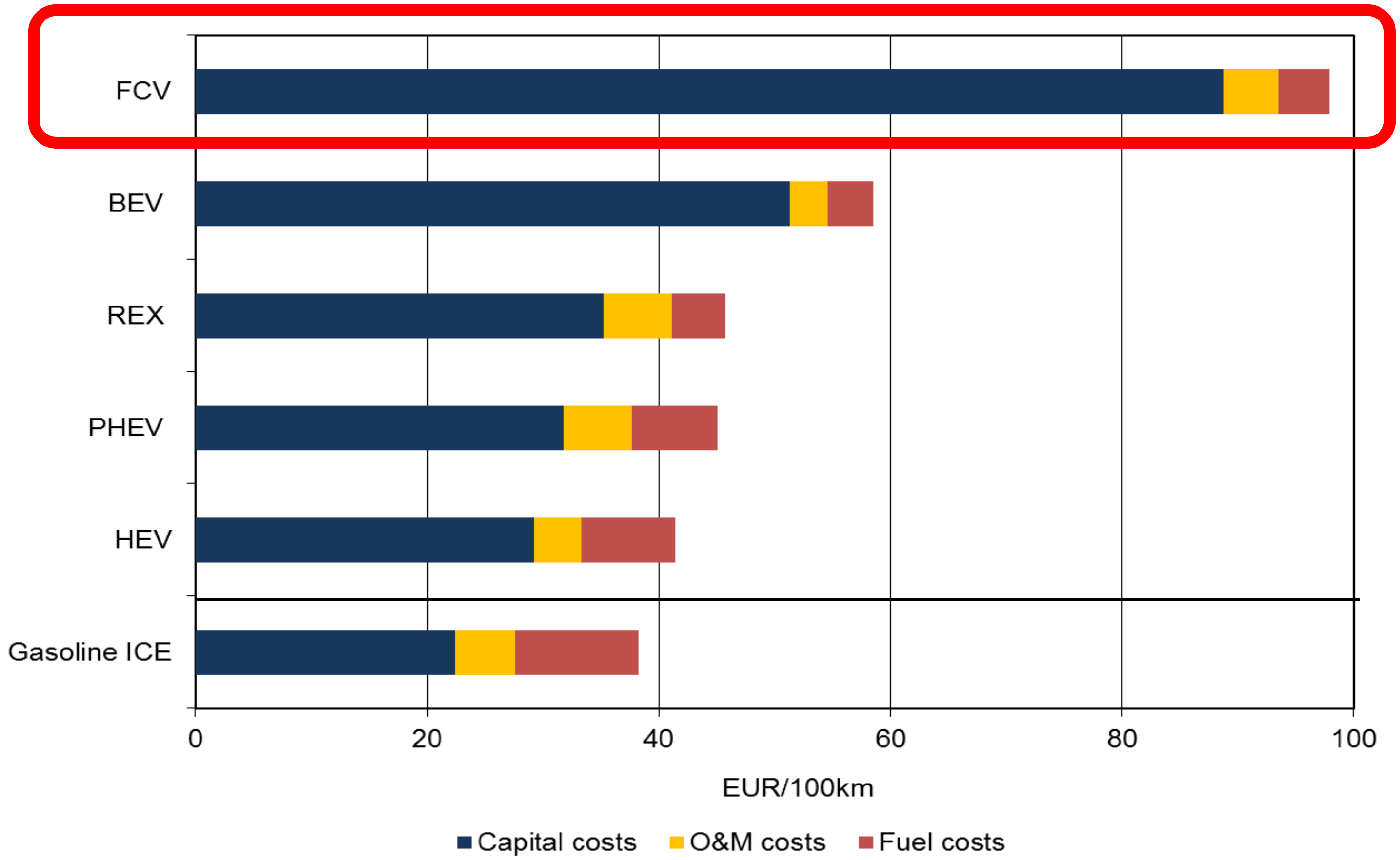
IC……investment costs [€/car]
α……..capital recovery factor
skm…..specific km driven per car per year [km/(car.yr)]
Pf……..fuel price incl. taxes [€/litre]
$C_{O\&M}$…operating and maintenance costs
FI……..fuel intensity [litre/100 km]

A capital recovery factor (α) is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Using an interest rate (z), the capital recovery factor is:

$$\alpha = \frac{z(1+z)^n}{(1+z)^n - 1}$$

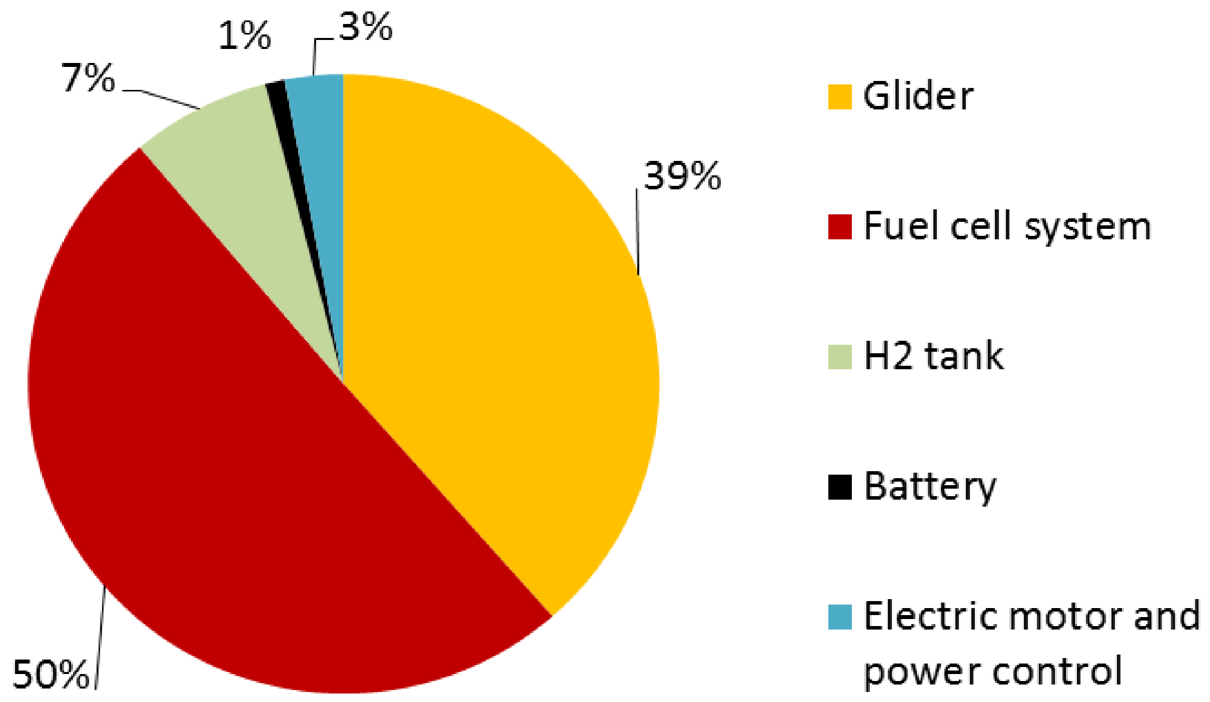
n…..the number of annuities received.

Economic aspects



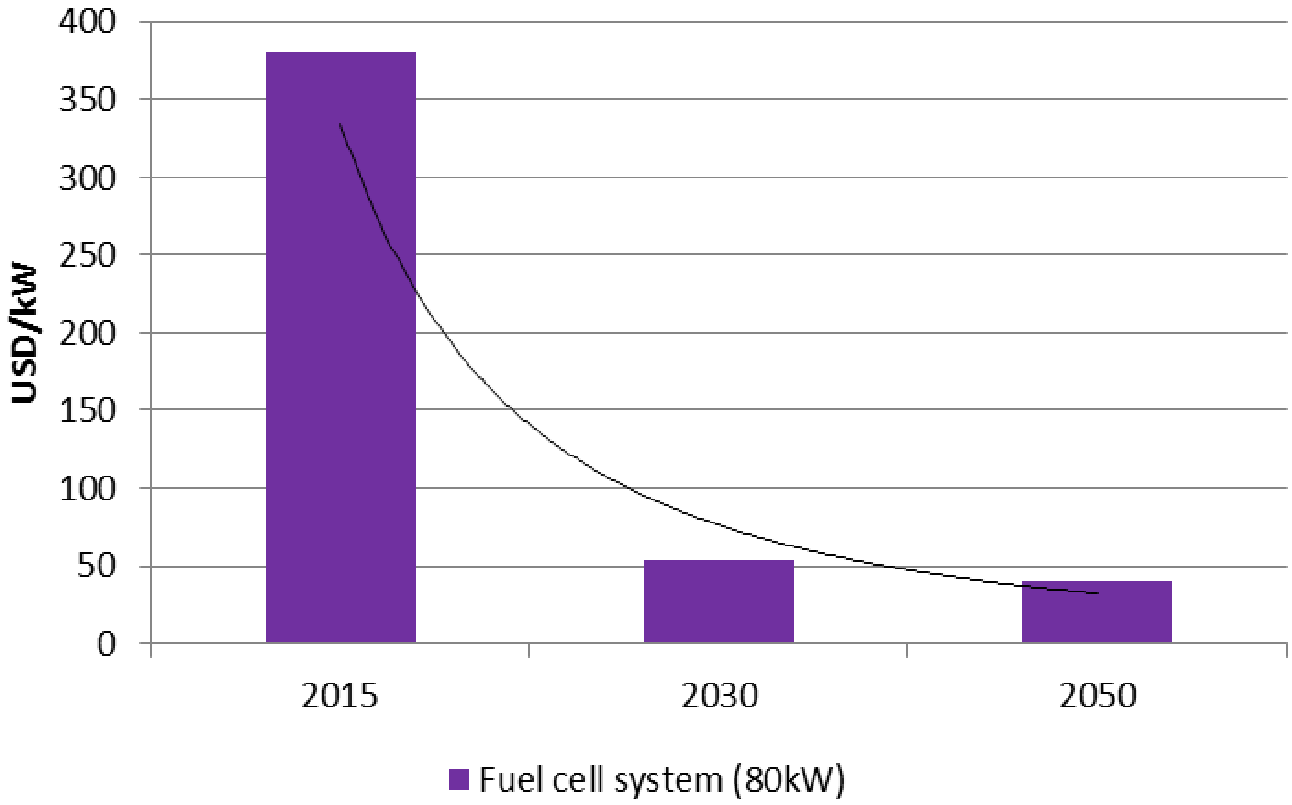
Total costs of service mobility of various types of EV in comparison to ICE cars

Fuel cell vehicles



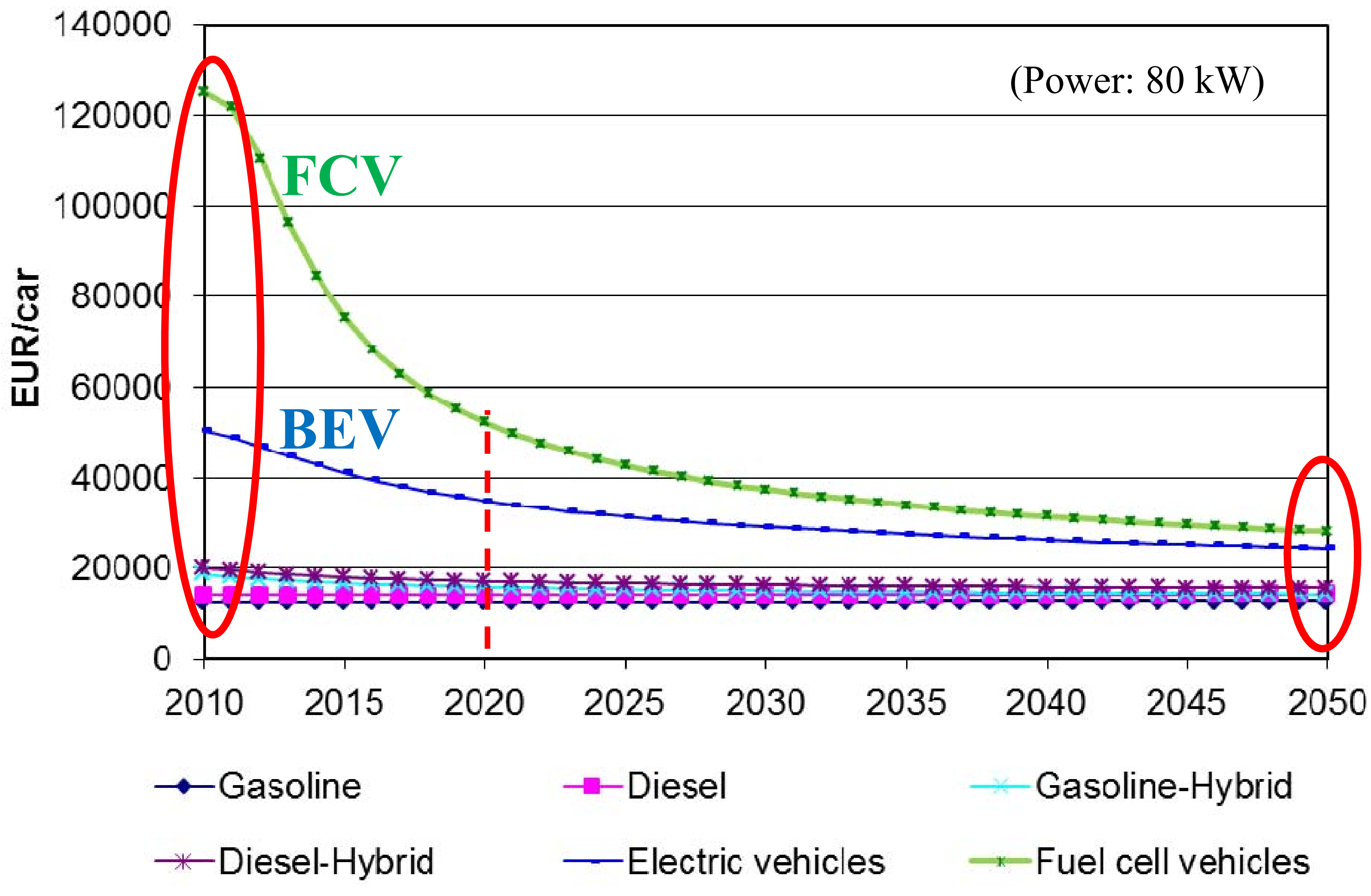
Structure of investment costs of fuel cell vehicles

Technological learning – Fuel cell

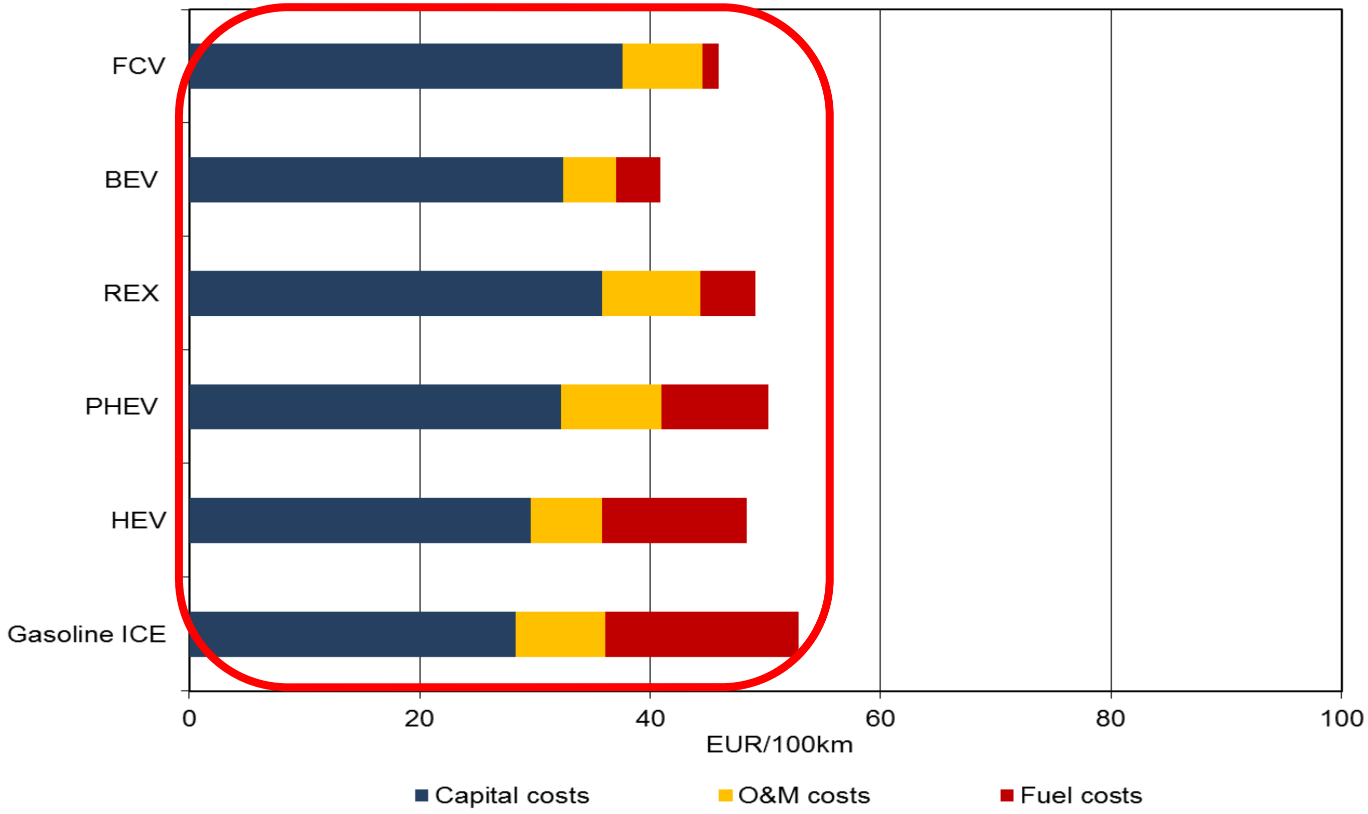


Development of the costs of the fuel cell system

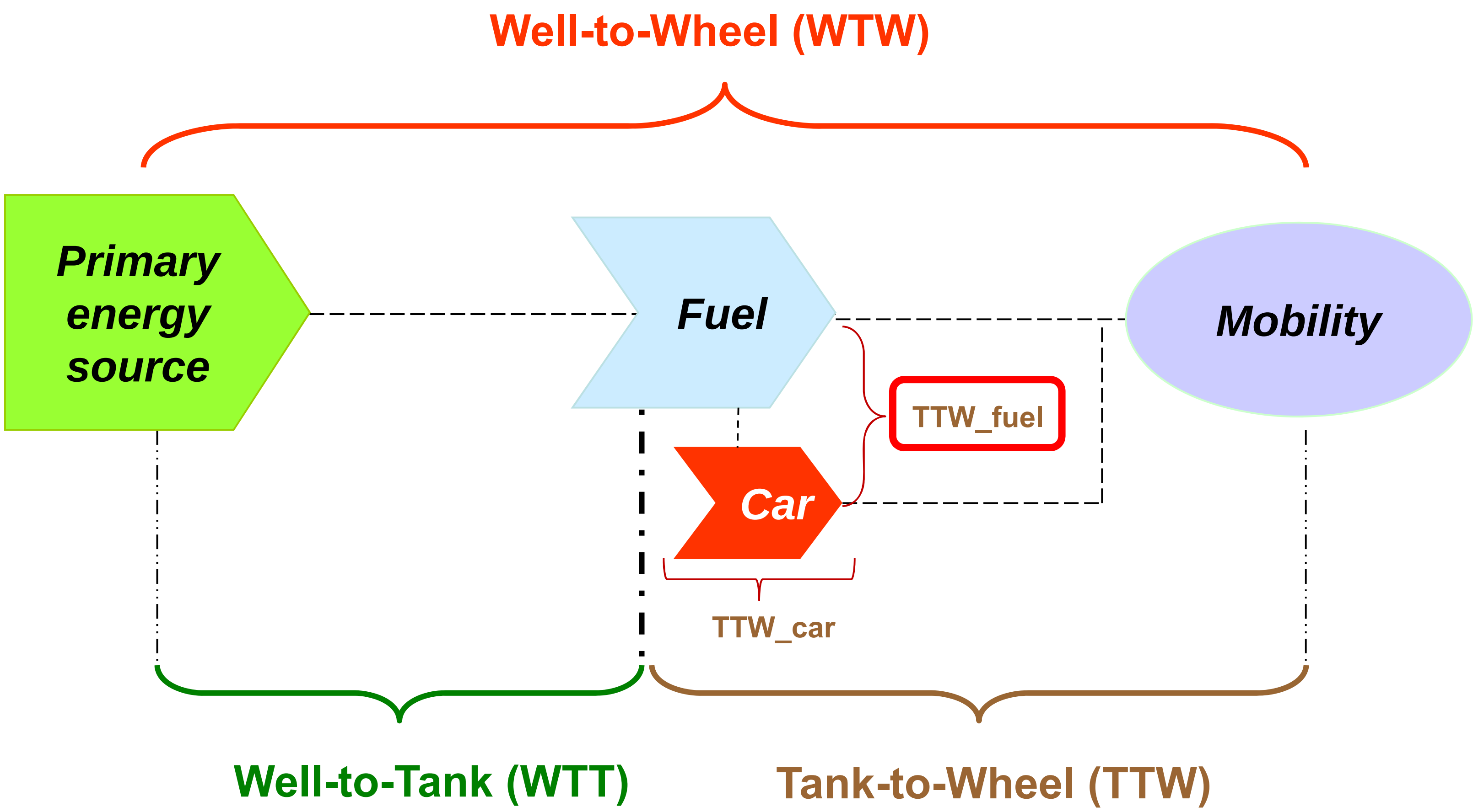
Scenario for development of investment costs



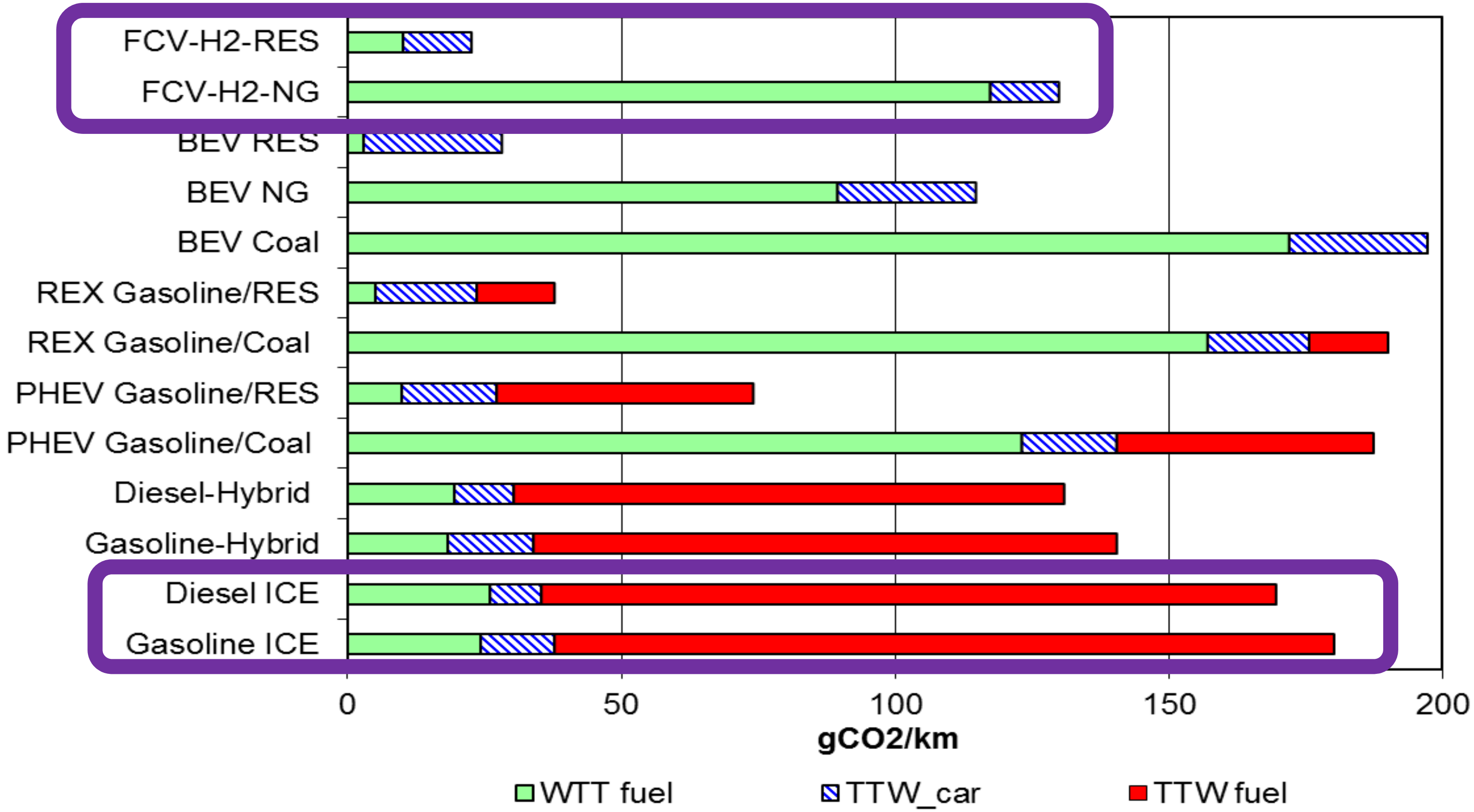
Costs of mobility – 2050



Environmental assessment



Environmental assessment



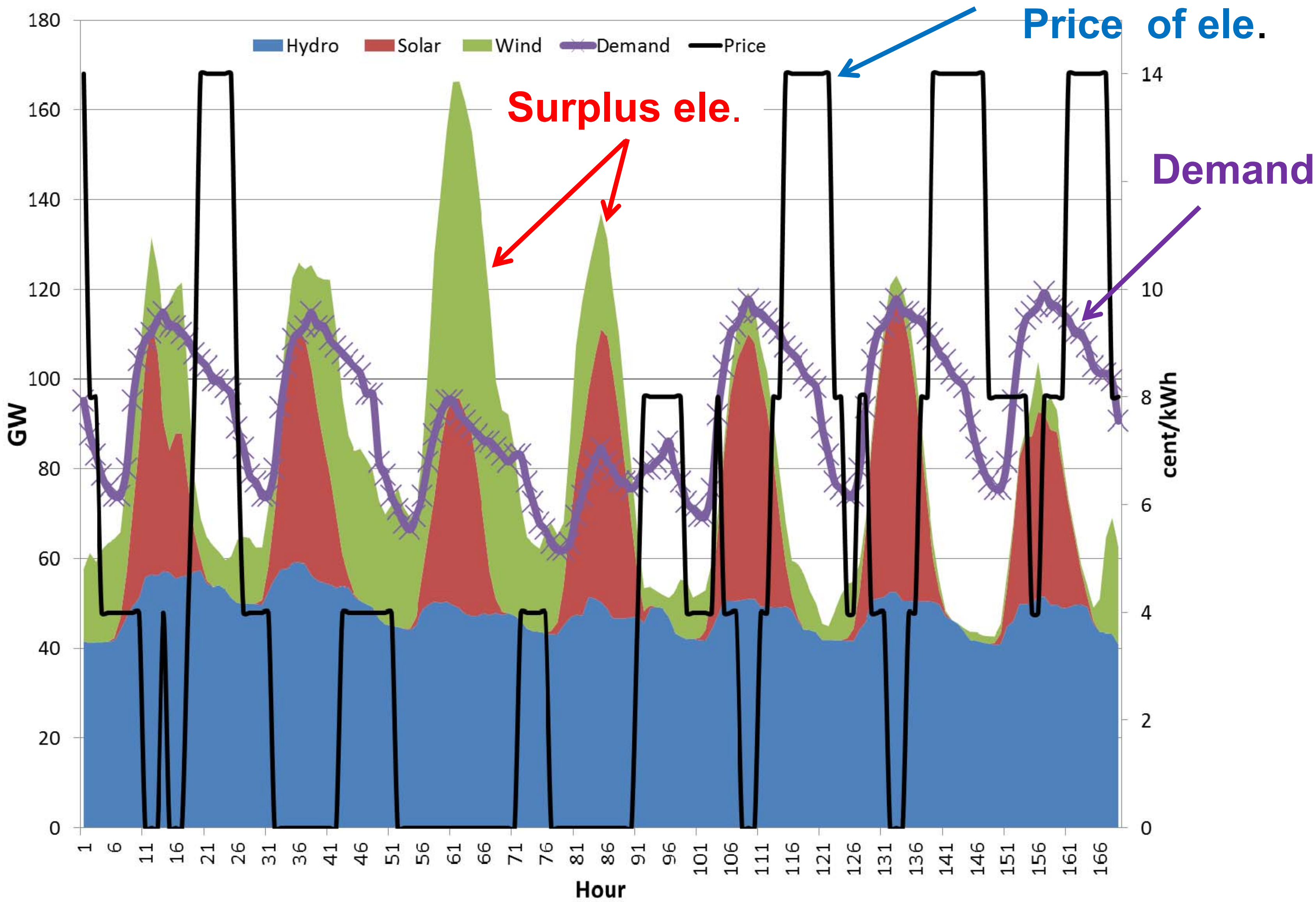
CO_2 emissions per km driven for various types of EV in comparison to conventional cars (power of car: 80kW)

Hydrogen as storage

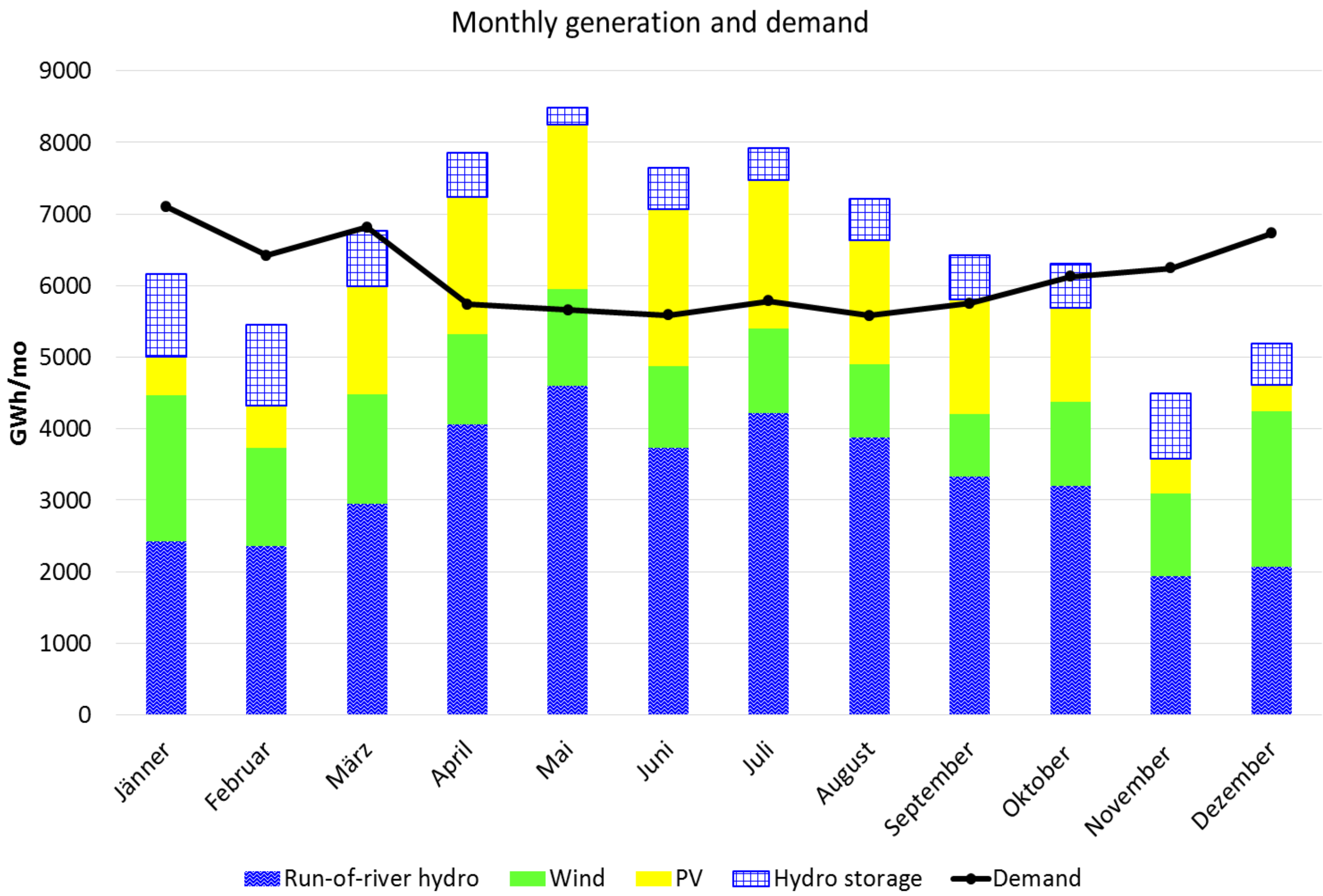
Hydrogen as storage

- Major challenges of global energy system:
  - sufficient and secure energy supply
  - reduction of energy-related greenhouse gas emissions
- Increase use of renewable energy sources (RES)
- How to cope with excess electricity from RES

Integrating large shares of renewable electricity

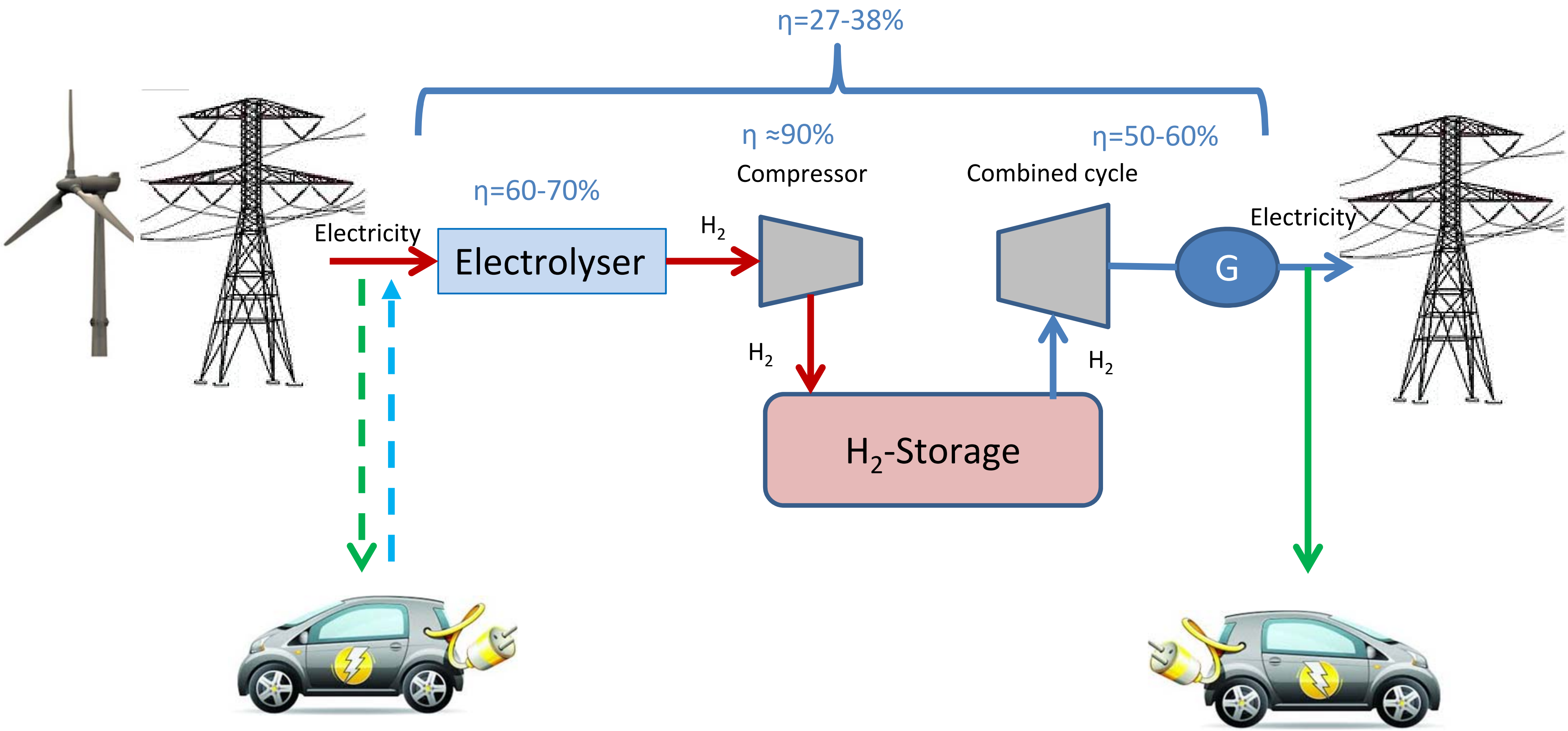


Integrating large shares of renewable electricity



Storage and fuel

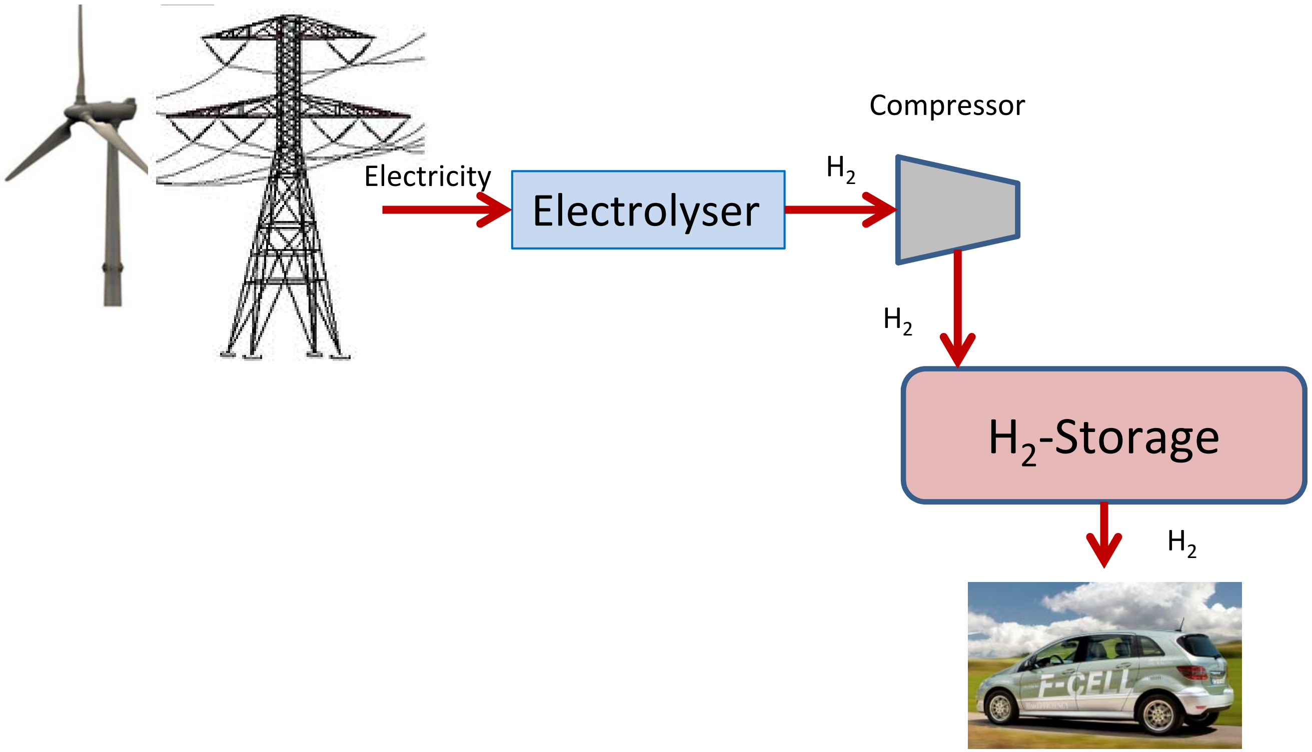
Very low roundtrip efficiency for electricity!



Battery degradation

Energy supply chains: Storage and/or use of RES for mobility

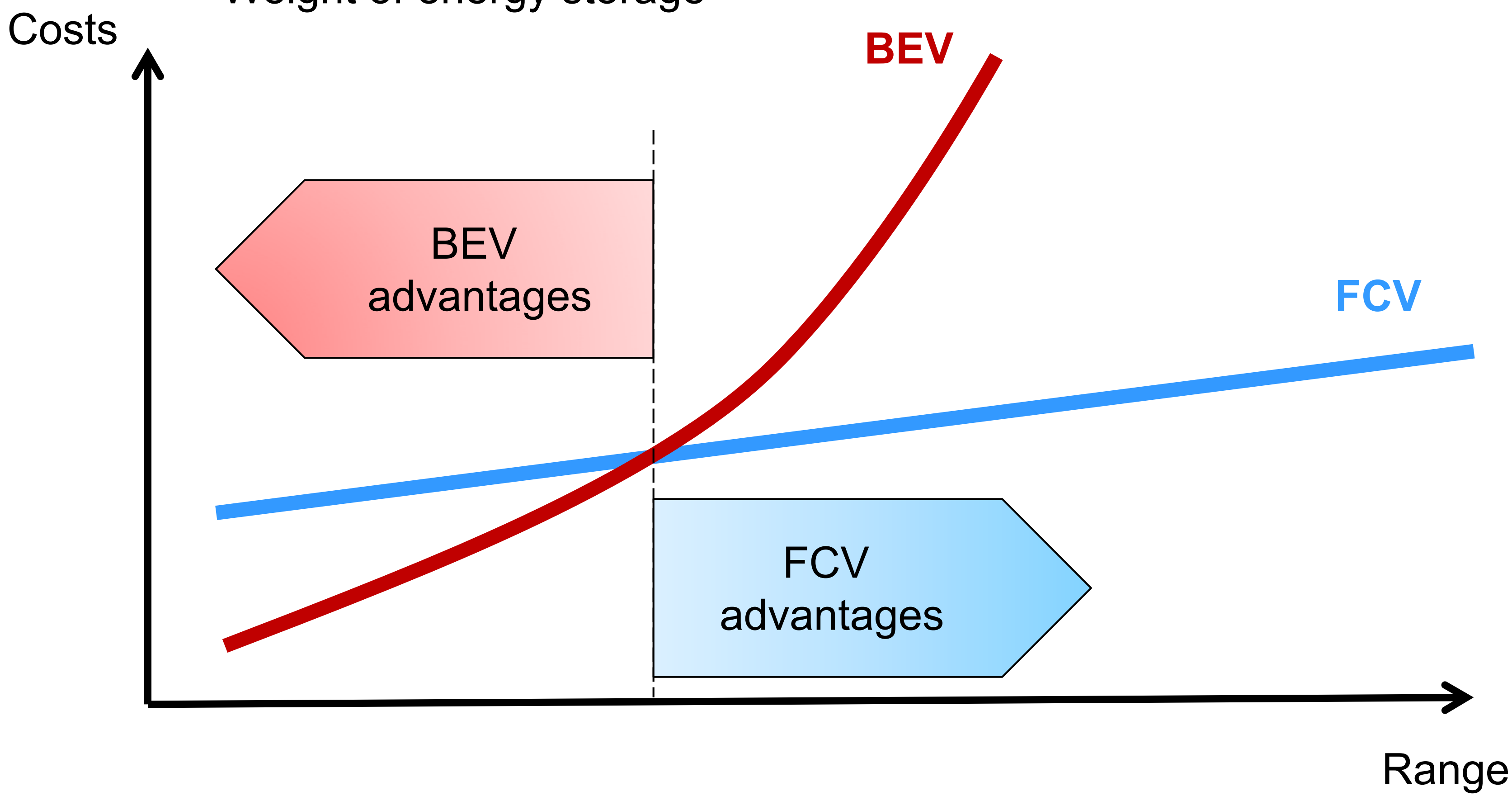
Hydrogen: storage and fuel



Energy supply chains: Storage and/or use of RES for mobility

FCVs vs BEVs

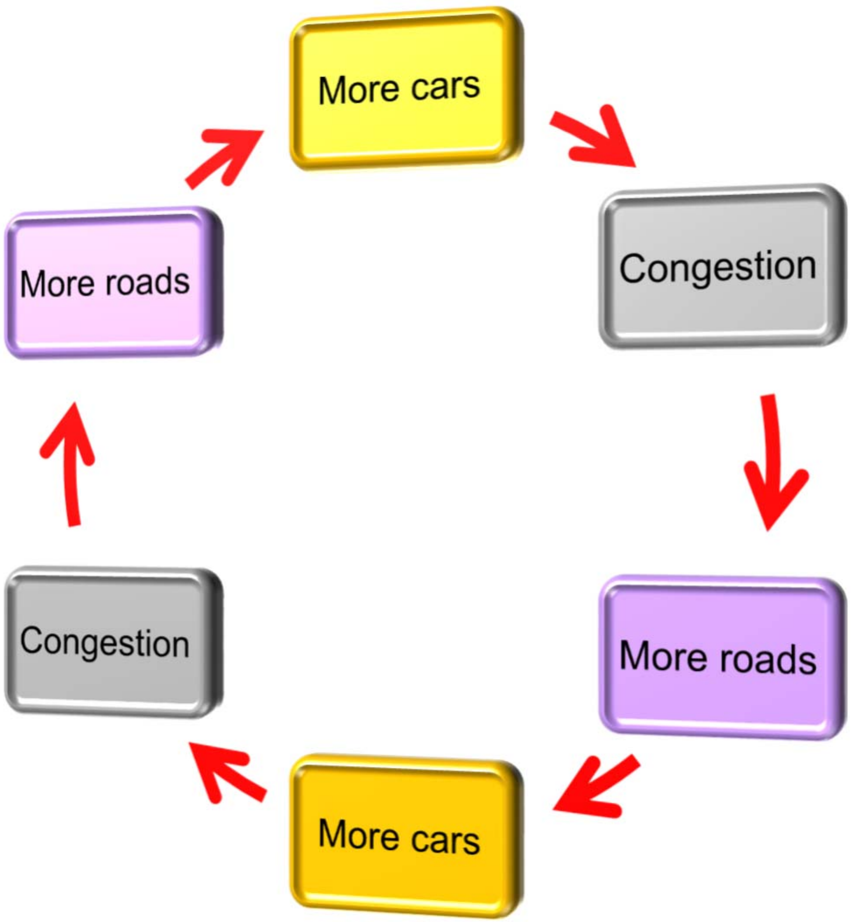
- Fuel efficiency
- Refuelling time
- Driving range
- Weight of energy storage



Conclusions

- Increasing electricity generation from variable RES
  $\Rightarrow$ need for new long-term storage options
- Need for environmentally friendly technologies in the transport sector
- Full environmental benefit – hydrogen from RES
- Major challenge – cost reduction and infrastructure development
- Stable policy framework, coordinated action between different stakeholders, standards – to derive economics of scale and reduce risks of the investment.

Car-oriented mobility

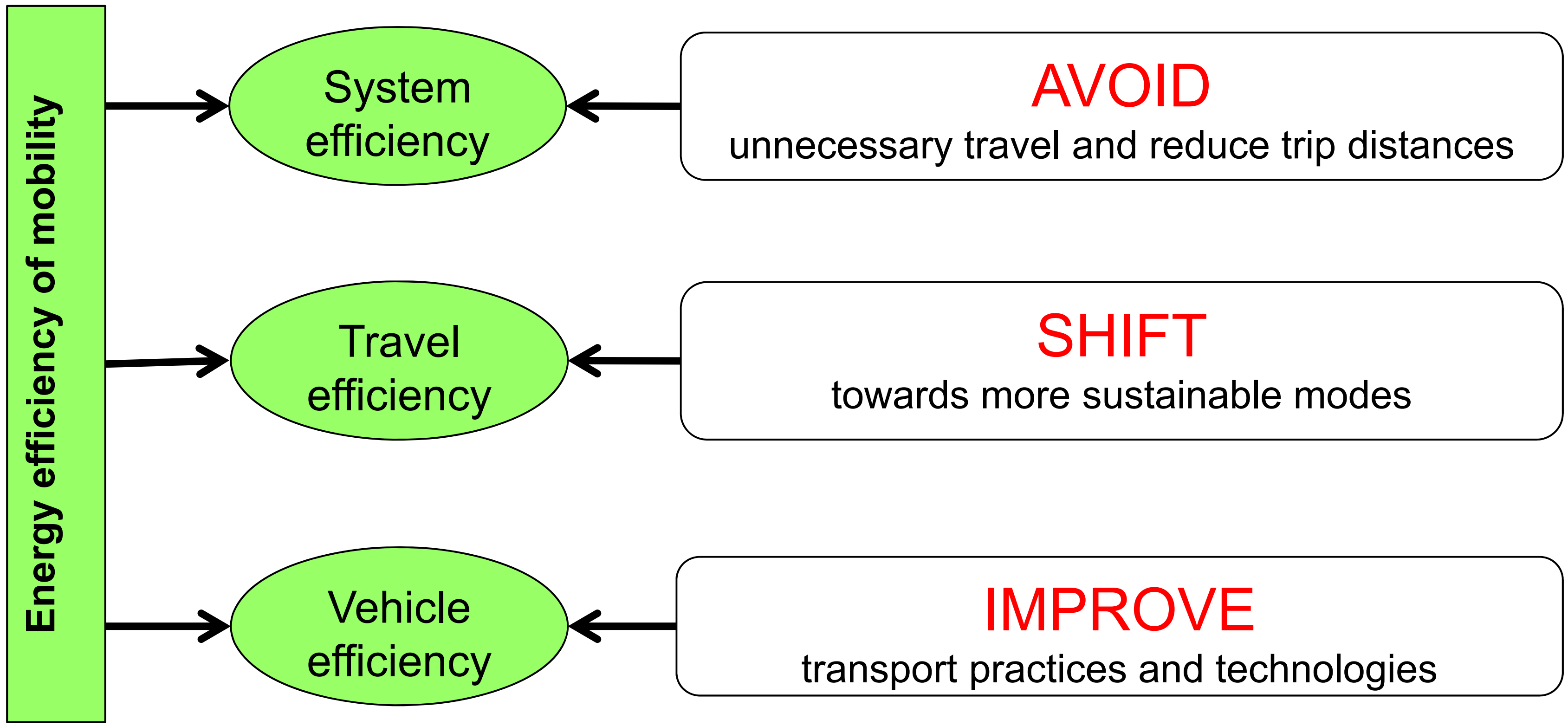


Conclusions

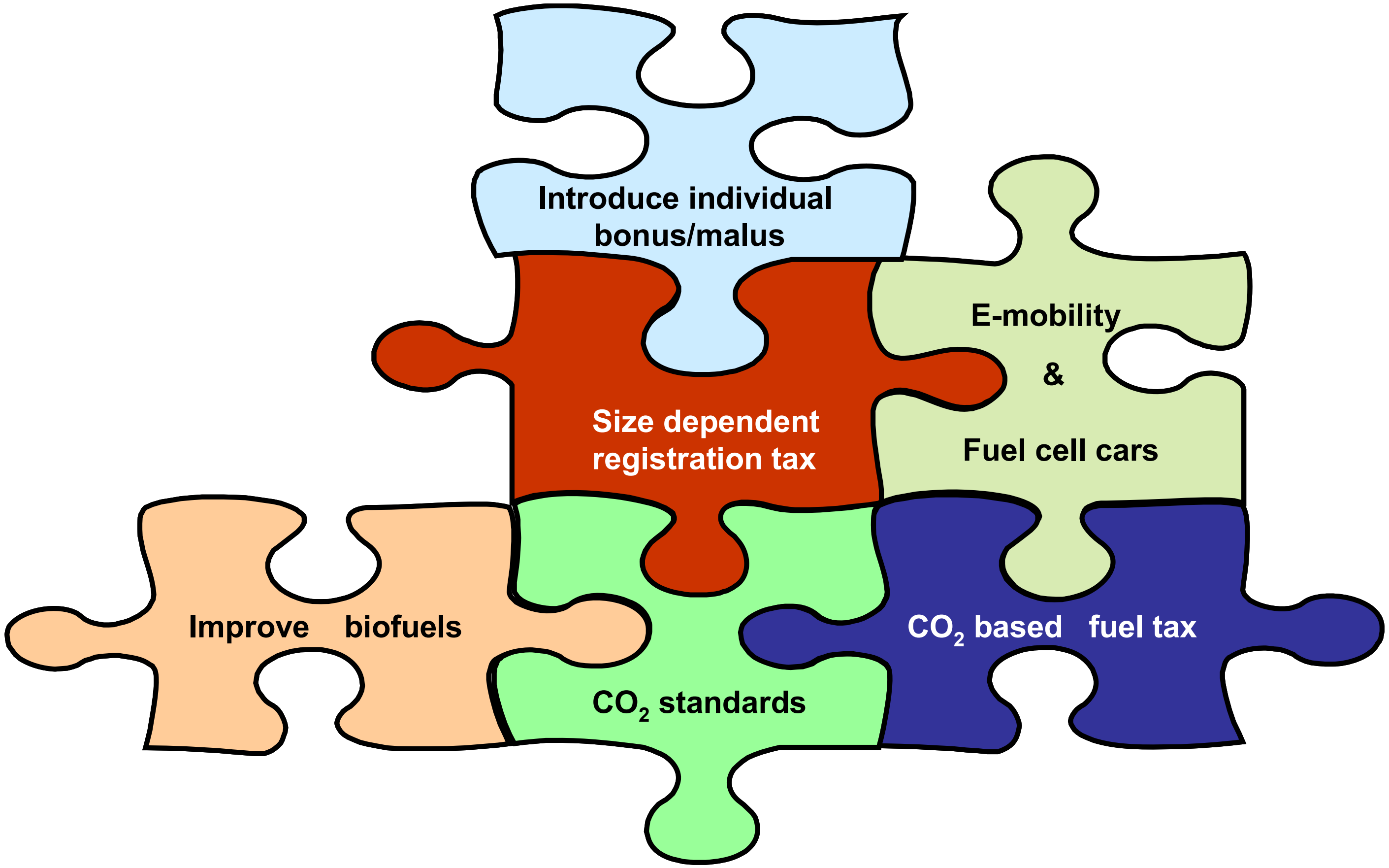
Car-oriented transport development

https://simotron.files.wordpress.com

Strategies for energy efficient mobility



Conclusions



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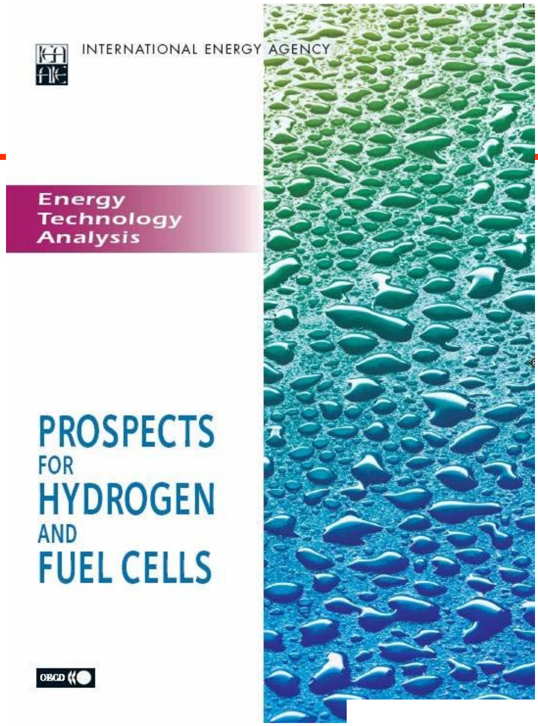

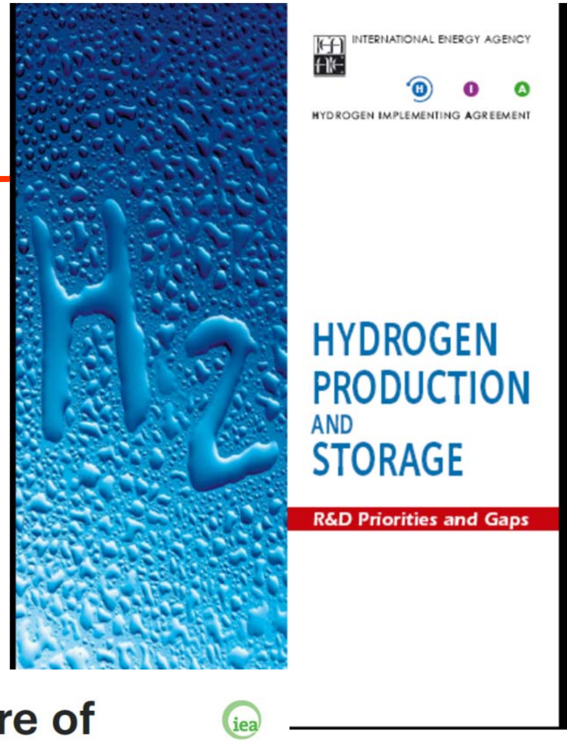

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GLOBAL TRENDS AND OUTLOOK FOR HYDROGEN

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