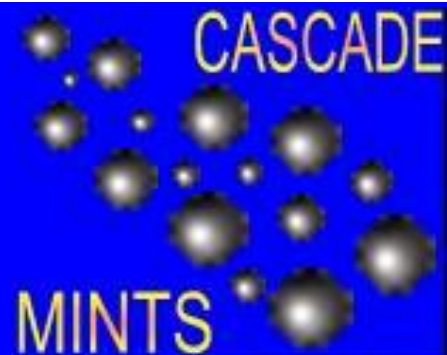

Prospects for a hydrogen economy: insights from model based analysis (CASCADE MINTS)

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Frankfurt Airport Intercity hotel

June 15th 2007



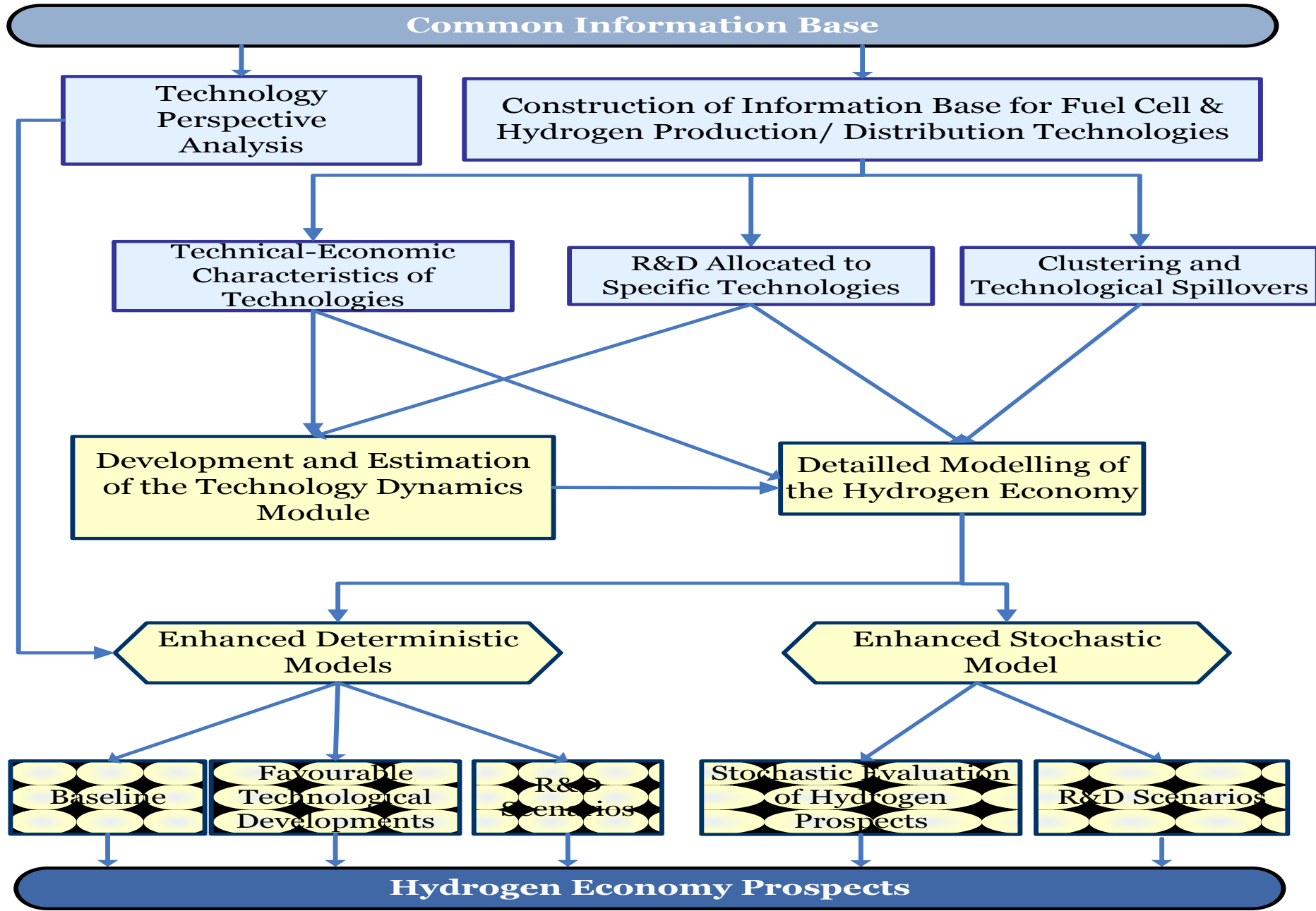
Main Objectives of the CASCADE MINTS

- Examine Hydrogen in the context of the whole energy system
 - Competition and complementarity with other energy system configurations
- Perspective analysis of the conditions under which a transition to an energy system dominated by hydrogen is possible
 - Timing, extent and possible obstacles
 - Systematic assessment of the likelihood of different paths
 - Analyse the technology dynamics in conjunction with appropriate policies - notably R&D efforts
- Deliver quantitative analysis

Project participants and models

Participant	Short Name	Model(s)		
		Name	Coverage	Type
Institute of Communications and Computer Systems of National Technical University of Athens	ICCS/NTUA	PRIMES	European	Partial equilibrium
		PROMETHEUS	World	Stochastic
Energy Research Centre of the Netherlands	ECN	MARKAL - WEU	European	Perfect foresight
Centre National de la Recherche Scientifique	CNRS	POLES	World	Partial equilibrium
International Institute for Applied System Analysis	IIASA - ECS	MESSAGE	World	Perfect foresight
Paul Scherrer Institut	PSI	MERGE-ETL	World	Perfect foresight
Centre for European Economic Research	ZEW	PACE -T	World	General equilibrium
German Aerospace Centre	DLR			

Project Articulation



Hydrogen related technologies considered in technology dynamics mechanisms

- **15 End-use technologies and components**

- **Transport : 11**
- **Covering:**
 - Mobile fuel cells stacks and systems
 - On board hydrogen storage (liquid and gaseous)
 - On board reformers
 - H2 Internal combustion engines
- **Stationary CHP applications: 4**
- **Covering:**
 - Small and large scale without reformer CHP fuel cells
 - Small and large scale with reformer CHP fuel cells

- **12 transportation / storage / distribution technologies :**

- **Covering:**
 - Pipelines
 - Service stations
 - Trucks for transporting H2
 - Liquefaction facilities
 - Liquid storage

Attributes considered:

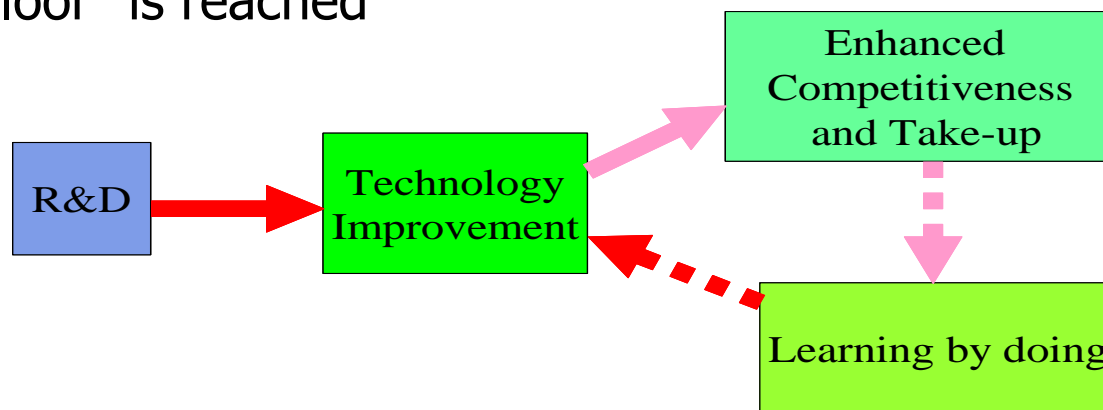
- **Costs** (capital, FOM, VOM)
- **Conversion efficiencies**
- **CO2 capture rates**
- **Life duration**

- **16 production technologies:**

- Coal gasification
- Gas steam reforming
- Solar methane reforming
- Oil partial oxidation
- Biomass pyrolysis
- Biomass gasification
- Nuclear HT
- Solar HT
- Electrolysis (grid)
- Electrolysis (nuclear)
- Electrolysis (wind)
- Options with CO2 capture
 - Gas steam reforming
 - Coal gasification
 - Biomass gasification
 - Oil oxidation

Technology dynamics – Two factor learning curves

- Both Learning-by-doing and Learning-by-Research
- Endogenising as much of the technical progress as possible
- Including “Clustering” as fully as available information will allow
- Constraint to technical possibilities as they emerge from perspective analysis (floor costs):
 - Saturation coefficient regulating the speed at which the “floor” is reached



Common assumptions

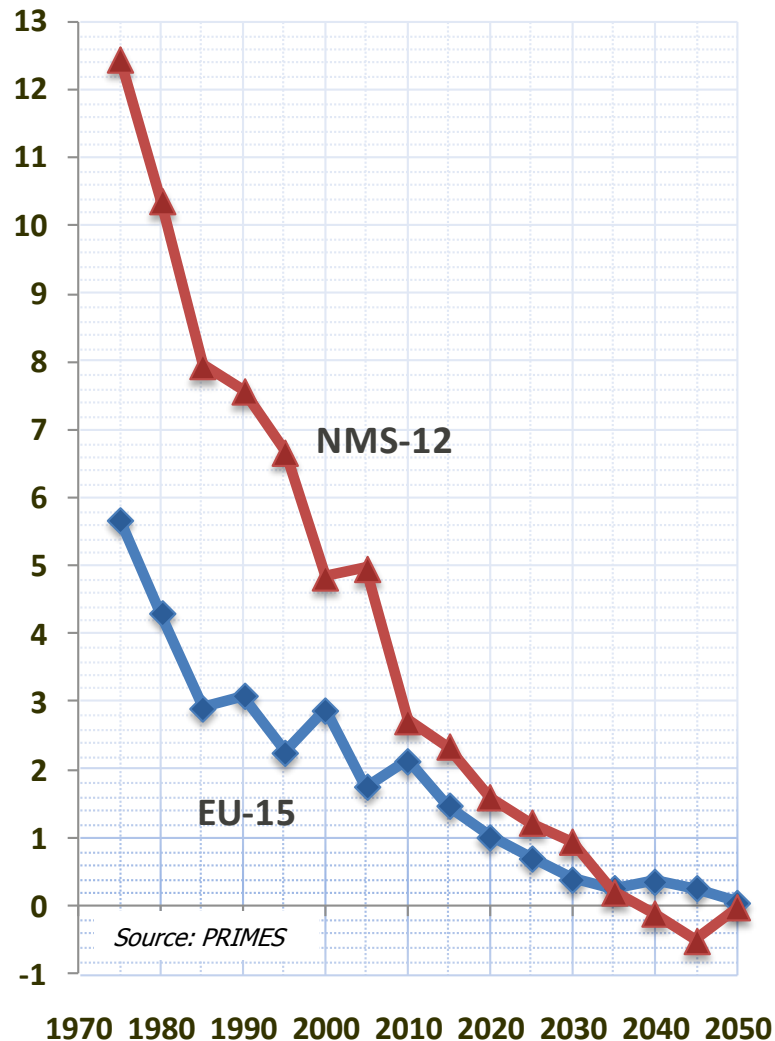
- **GDP growth:**
 - Until 2030
 - World: 3.2%/yr
 - Europe: 2.1%/yr
 - Rest of OECD: 2.3%/yr
 - Developing countries: 4.2%/yr
 - In the period 2030-2050
 - World: 2.2%/yr
 - Europe: 1.4%/yr
 - Rest of OECD: 1.5%/yr
 - Developing countries: 2.6%/yr
- **Population growth:**
 - Until 2030
 - World: 1.1%/yr
 - Europe: 0.1%/yr
 - Rest of OECD: 0.6%/yr
 - Developing countries: 1.2%/yr
 - In the period 2030-2050
 - World: 0.3%/yr
 - Europe: -0.2%/yr
 - Rest of OECD: 1.5%/yr
 - Developing countries: 0.6%/yr
- **Oil price:**
 - In 2030: 70 €/05/bl
 - In 2050: 120 €/05/bl
- **Average carbon value (2005-2050)**
 - Europe: 40 €/05/tn of CO₂
 - Rest of OECD: 25 €/05/tn of CO₂
 - Developing countries: 10 €/05/tn of CO₂

Scenarios

- Baseline
 - Broadly similar key assumptions
 - Median climate policy stance for the different regions of the world
 - Common technology-by-technology R&D Outlook and improvement
- Technology Story Scenarios
 - Favourable technological developments combined with supportive policies to produce a more rapid transformation of the energy system towards a hydrogen economy
- R&D Scenarios
 - Quantitative analysis of the possible role of R&D in enabling or accelerating the introduction of H₂ as a major vector in energy balances

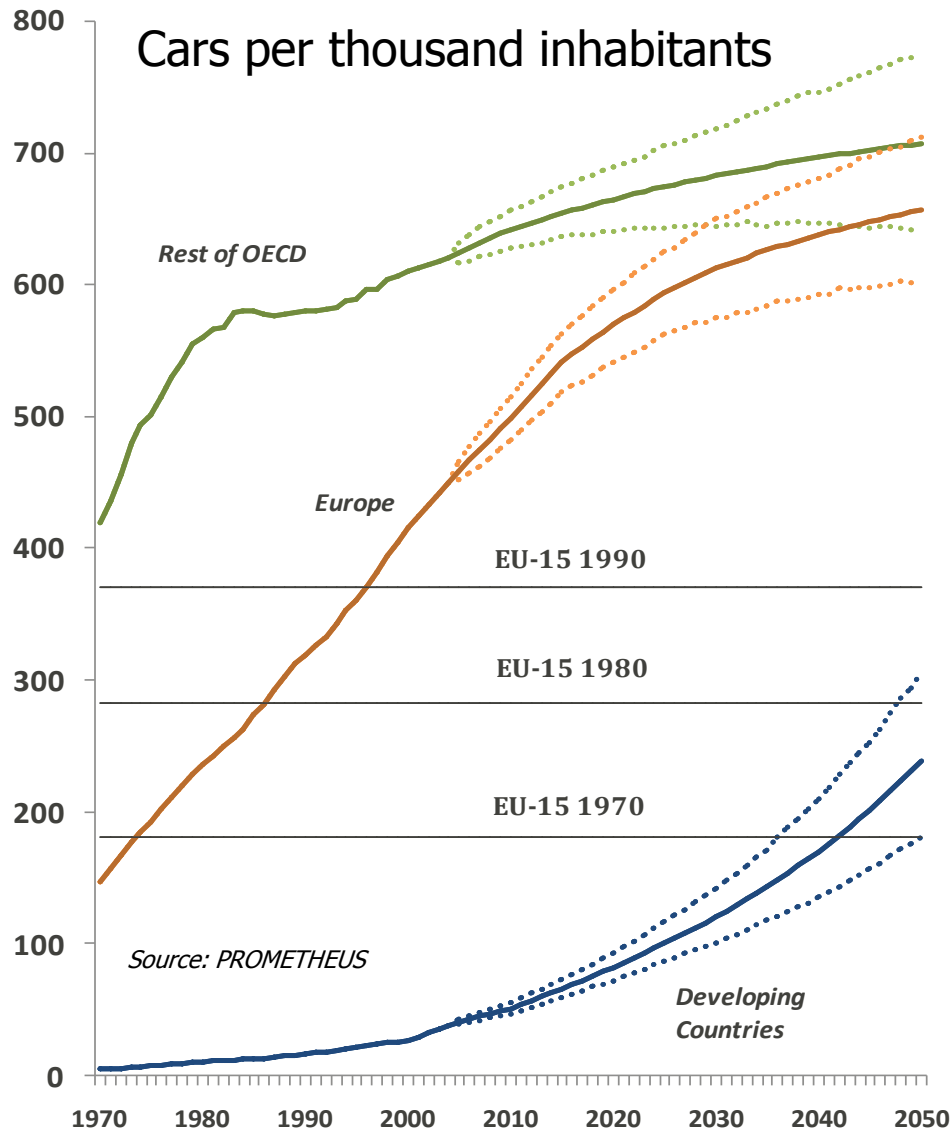
EU vehicle stock evolution

% Annual growth rate of car stock



- EU-15 saturation effects pronounced after 2020
- NMS-12:
 - Currently around the middle of the penetration curve with ownership increasing rapidly.
 - The first real signs of saturation will occur after 2030
- Ownership rates per 000 inhabitants in 2050:
 - EU-15 665 cars,
 - NMS-12 630 cars

Car ownership prospects



Developing countries:

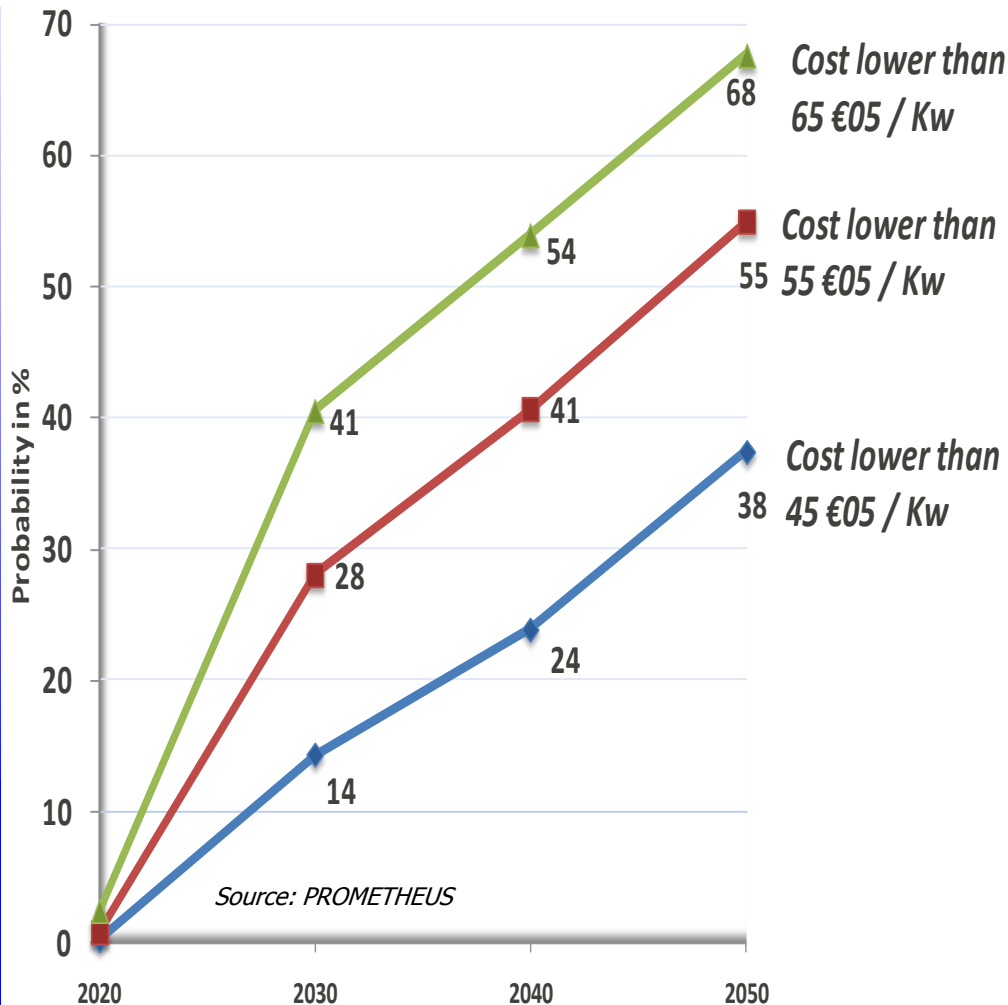
- Currently experiencing take-off in car ownership, suggesting similar patterns as those experienced in developed countries several decades ago
- There is a 95% probability of exceeding the rates experienced in EU-15 in 1970 and a 9% probability of exceeding the equivalent figure of 1980

Very high probabilities of a private car based road transport for the world

- the main uncertainty remaining only on the timing of the different phases of development

Technological improvement prospects

Probability that mobile fuel cell stack and system costs be lower than certain levels



- 2020: technical progress unlikely to occur to a sufficient degree to allow introduction of fuel cells in anything but niche markets.
- 2030: the likelihood of different success levels improves markedly.
- 2040: More than even probability of technological success of some sort.
- 2050:
 - Two-in-three probability of a valid choice in road transport
 - More than even chance that there will be genuinely competitive.
 - Probability of a big breakthrough less than 40%.
 - Probability of a complete technical failure (costs above 80€/Kw) 20%

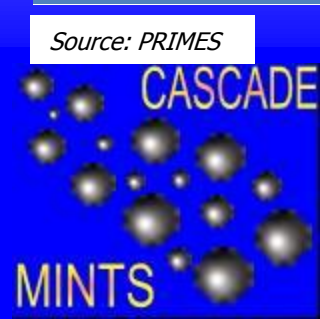
Competitiveness of alternative road transport options (EU-27)

Cost per vehicle kilometre (cents of €05) assuming 15000 km/yr

	2005	2010	2020	2030	2040	2050
Gasoline ICE	38.5	41.2	41.2	41.2	42.1	43.0
Diesel ICE	37.0	38.6	39.7	40.1	41.1	42.2
Hybrid	41.7	43.3	42.4	41.9	42.1	42.4
Plug-in hybrid	49.4	51.7	49.5	47.0	46.1	45.3
Electric car	56.5	60.2	56.3	50.9	48.6	46.4
H2 ICE	45.7	45.2	42.8	41.1	41.0	42.5
Fuel cells	2392.9	717.8	76.4	48.5	44.6	42.1
Fuel cells on board reformer	2884.6	948.4	117.1	68.1	54.9	47.4

Source: PRIMES

- introduction of hydrogen in the automotive sector triggers gradual increase in hydrogen taxation



Competitiveness prospects

% Probability that a given option has lowest cost per vehicle km for 15000km/yr

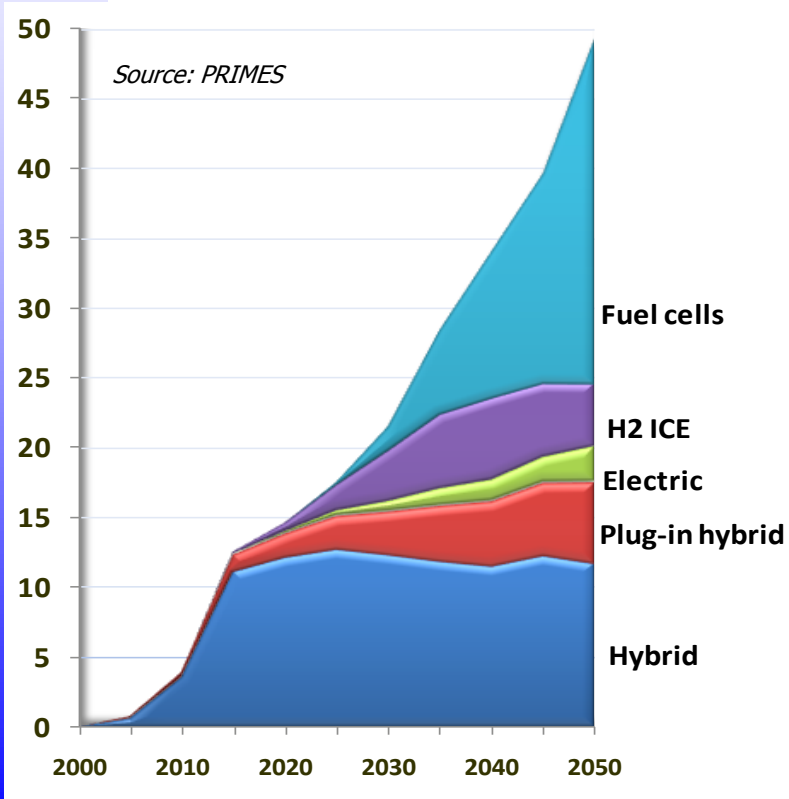
Car type	Europe		Rest of OECD		Rest of the World	
	2030	2050	2030	2050	2030	2050
Conventional	97.4	80.6	100.0	79.2	100.0	78.1
Hybrids/Electric	0.0	4.2	0.0	0.9	0.0	0.7
H2 ICE	2.2	2.8	0.0	10.4	0.0	6.1
Fuel cells	0.4	12.4	0.0	9.5	0.0	15.1

% Probability that a given option has lowest cost per vehicle km for 25000km/yr

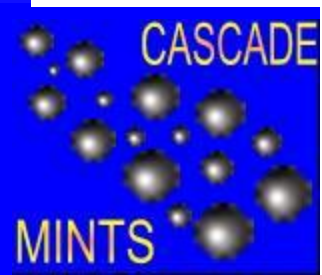
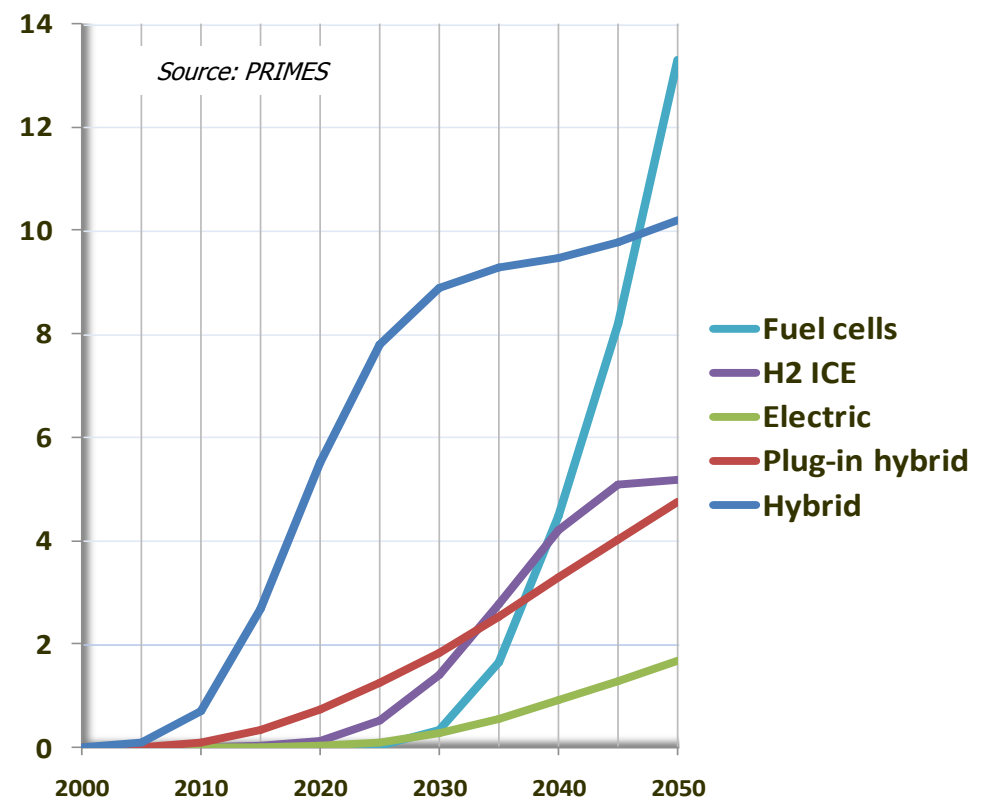
Car type	Europe		Rest of OECD		Rest of the World	
	2030	2050	2030	2050	2030	2050
Conventional	92.7	72.9	100.0	78.0	100.0	71.2
Hybrids/Electric	0.0	5.4	0.0	0.0	0.0	0.0
H2 ICE	3.4	1.9	0.0	6.2	0.0	2.9
Fuel cells	3.9	19.9	0.0	15.8	0.0	25.9

Technology penetration in EU-27 light vehicles market

% in new car registrations



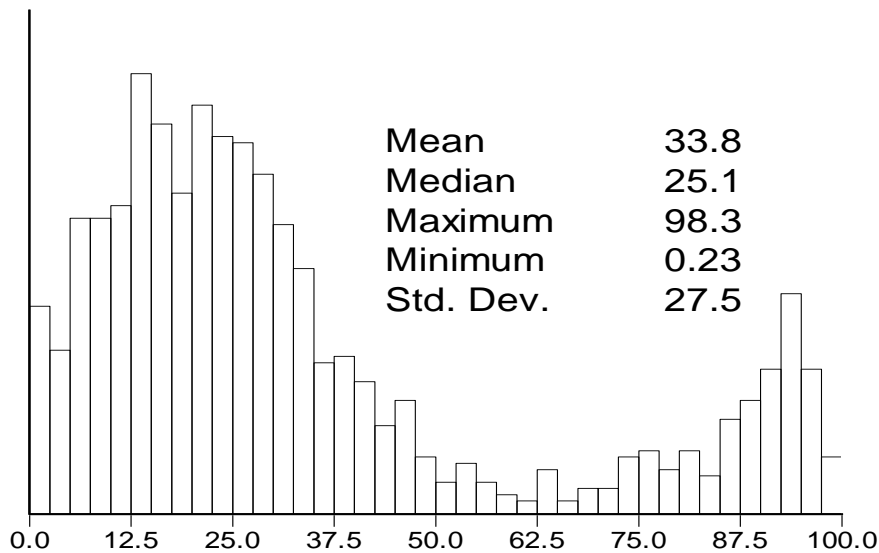
% in car stock



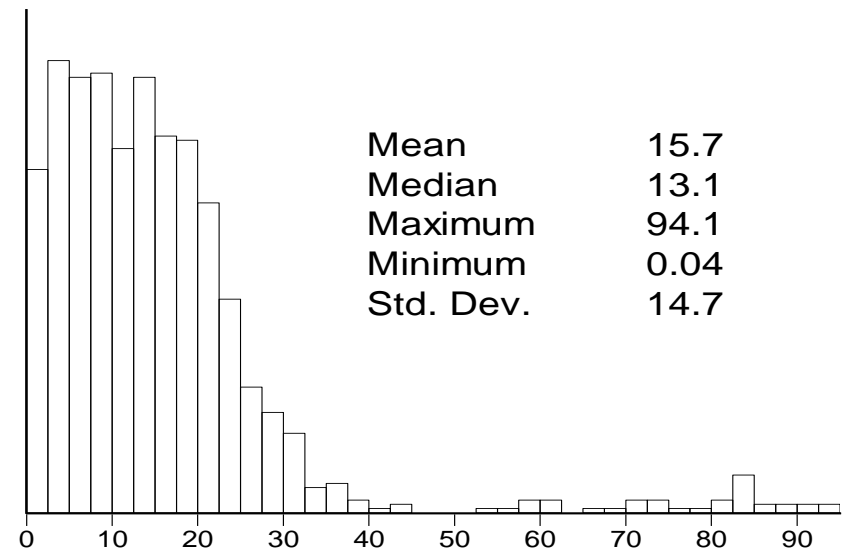
Variability in success rates (2050)

Probability distributions of fuel cell new registrations shares

Europe

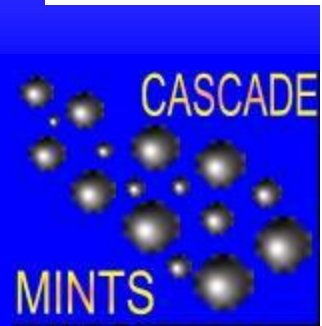


Developing countries



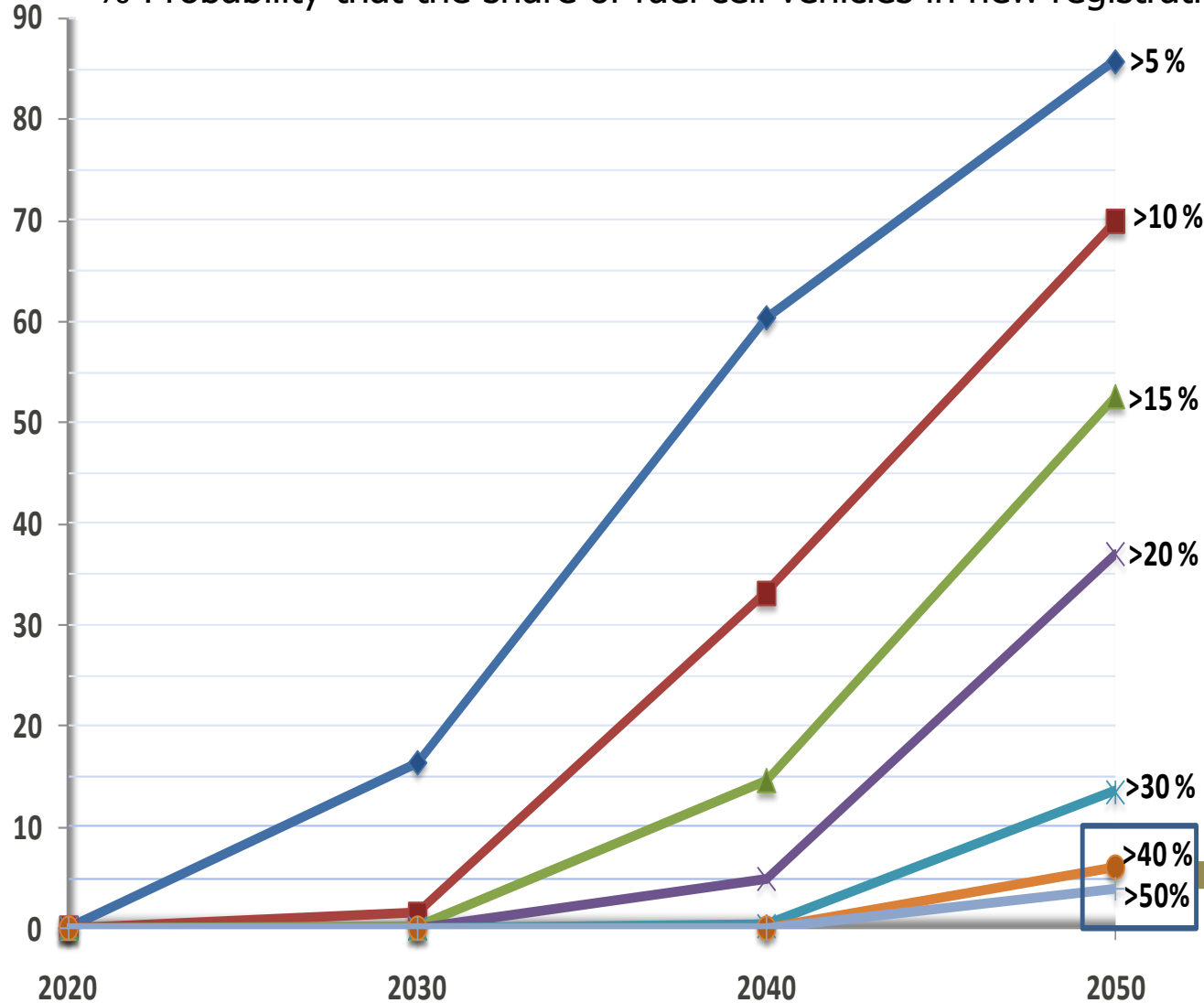
Source: PROMETHEUS

- Bimodality and a probability trough around 50% with a resurgence of probability densities for higher shares.
- Primarily due to the social network effects:
 - in some cases technological success is combined with accelerated social acceptance thus snowballing into very high penetration rates

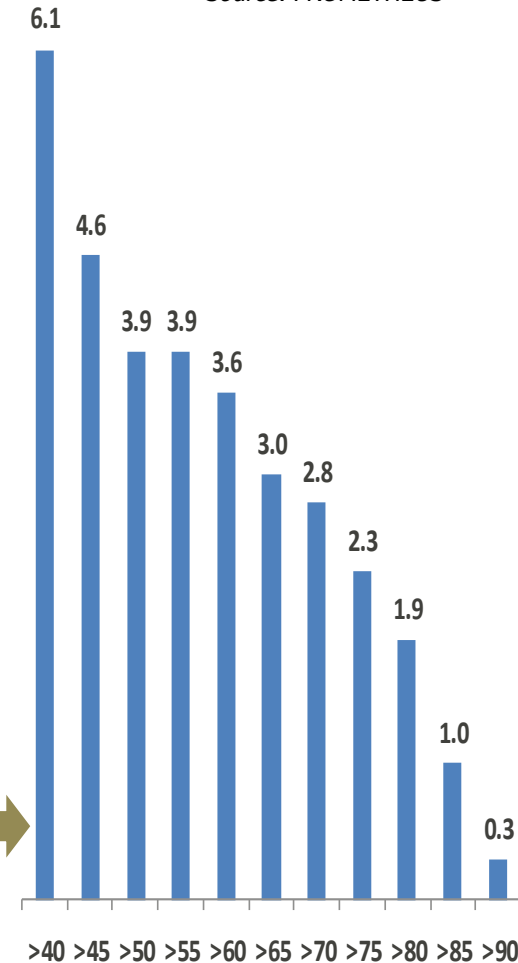


Worldwide prospects evolution

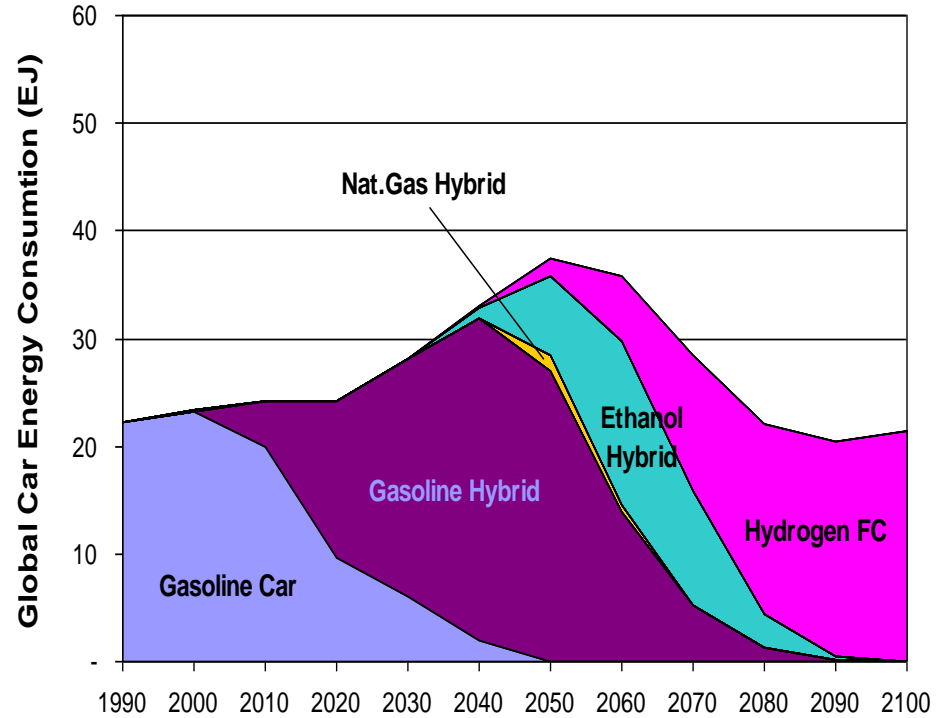
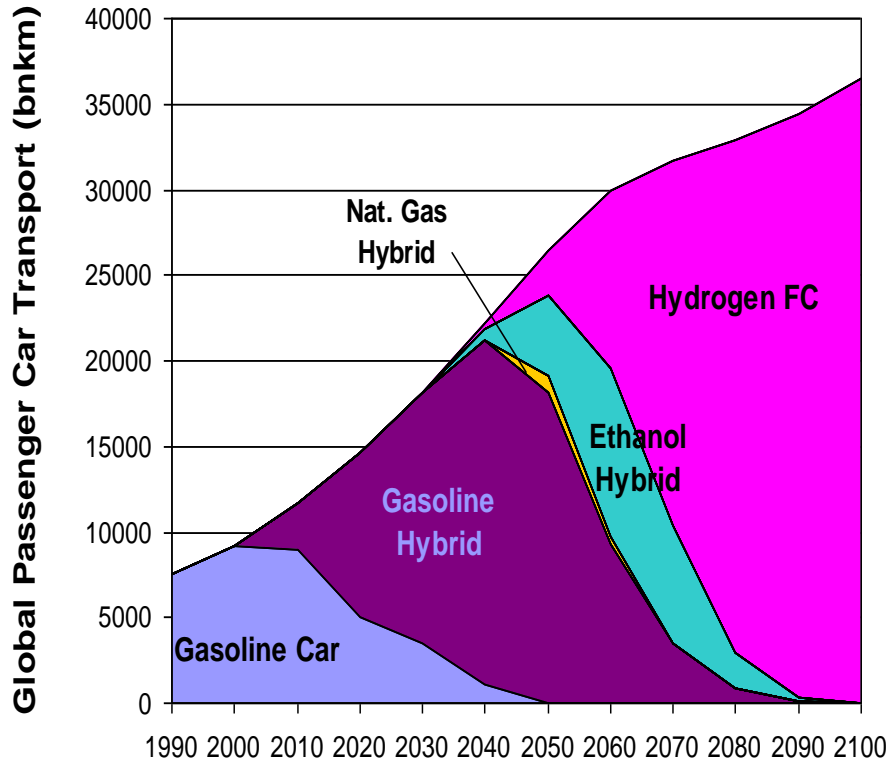
% Probability that the share of fuel cell vehicles in new registrations will exceed certain levels



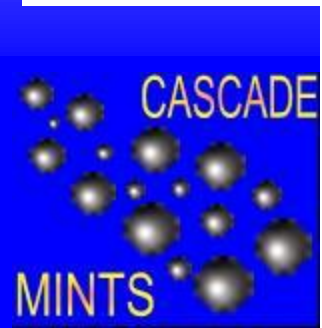
Source: PROMETHEUS



Longer term prospects of hydrogen in transport

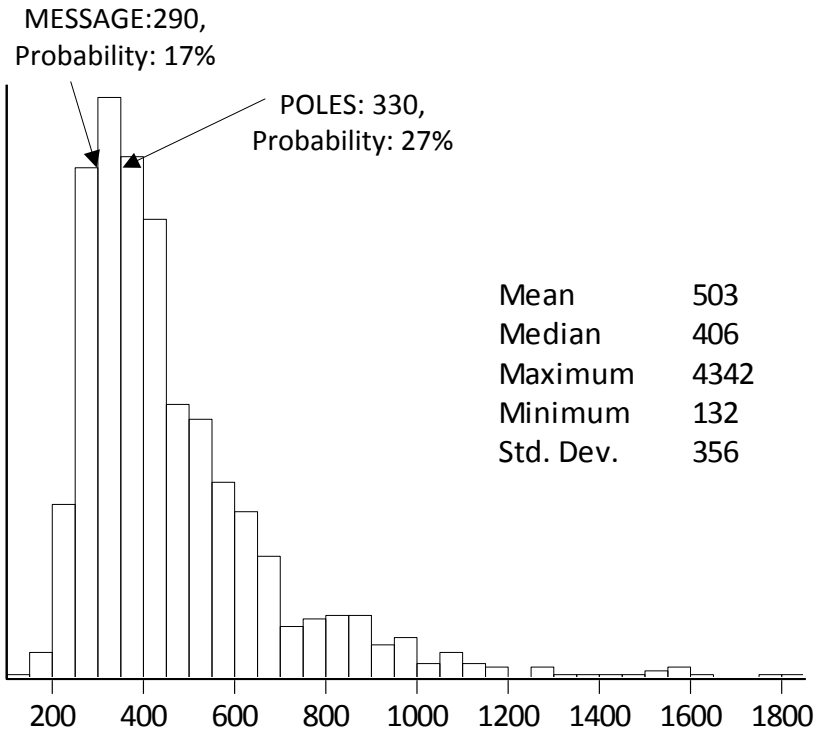


Source: MESSAGE

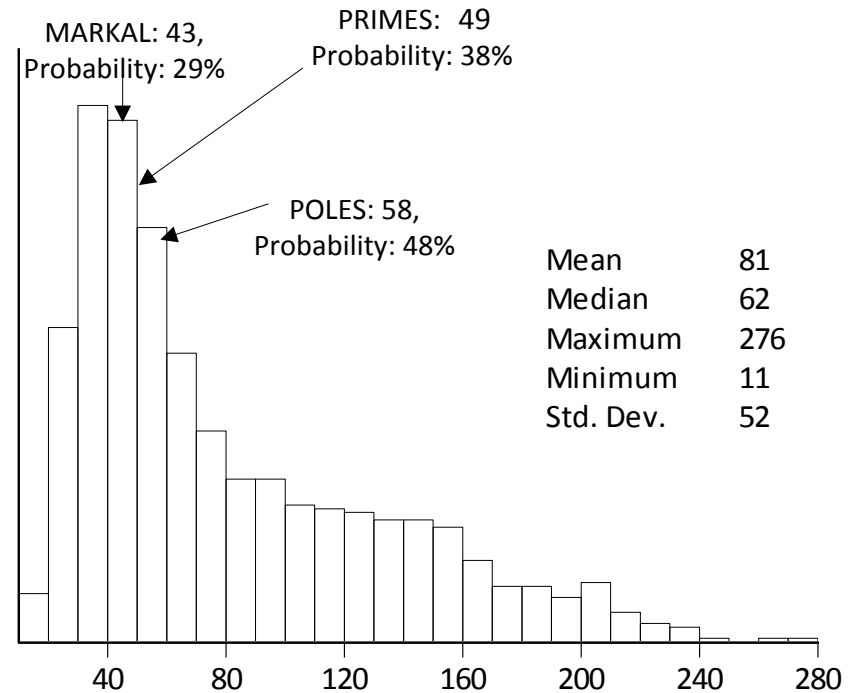


Hydrogen demand in 2050 (Mtoe)

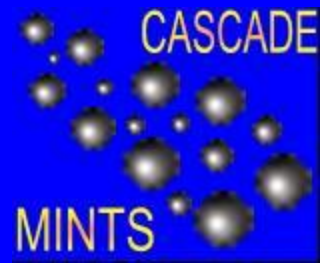
WORLD



EUROPE

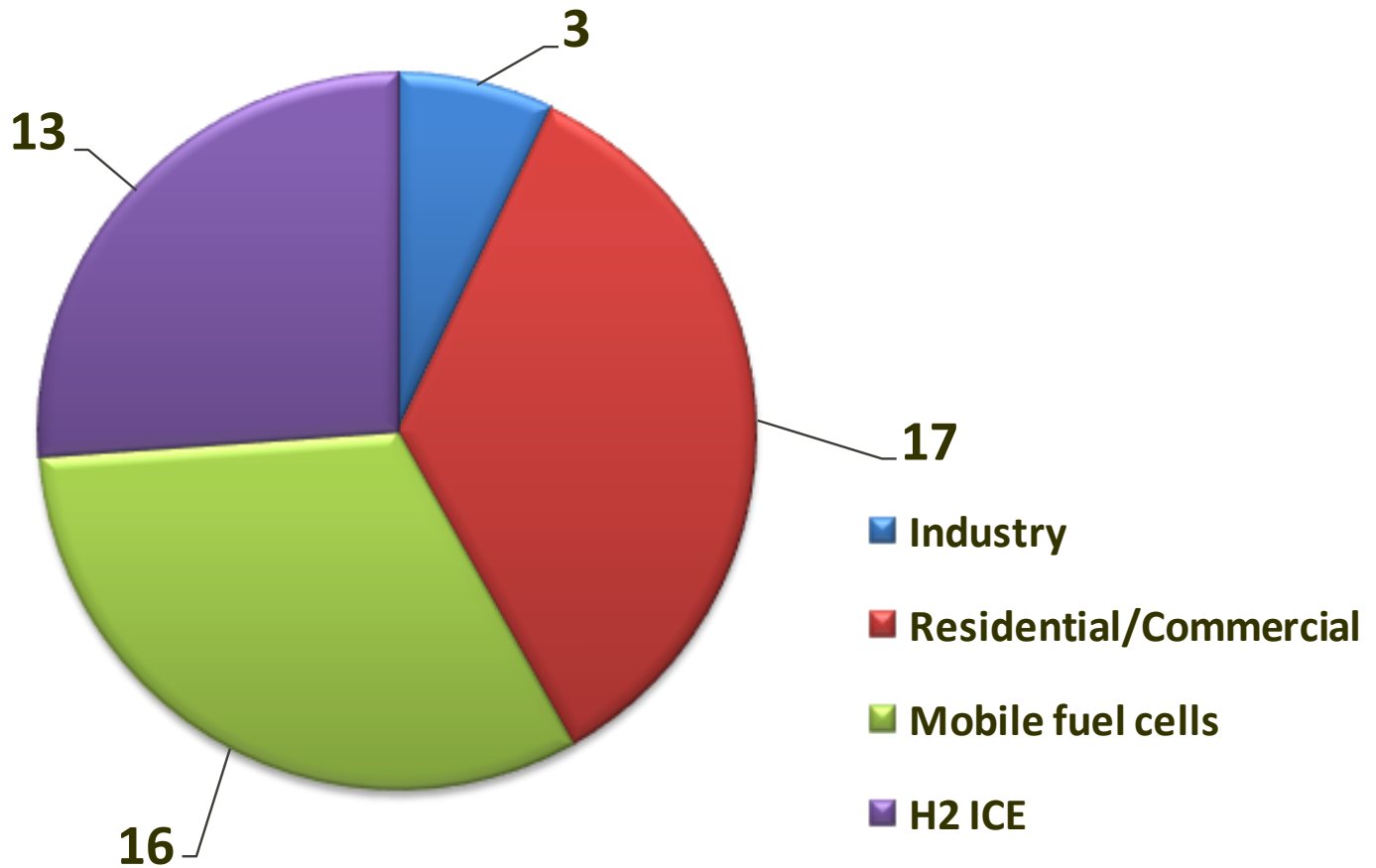


Source: PROMETHEUS



- PROMETHEUS means considerably higher than deterministic model predictions.
 - Influence of small possibilities of major technico-economic breakthroughs.
- None of the baseline predictions can be considered as an outlier, they are generally close to distribution modes

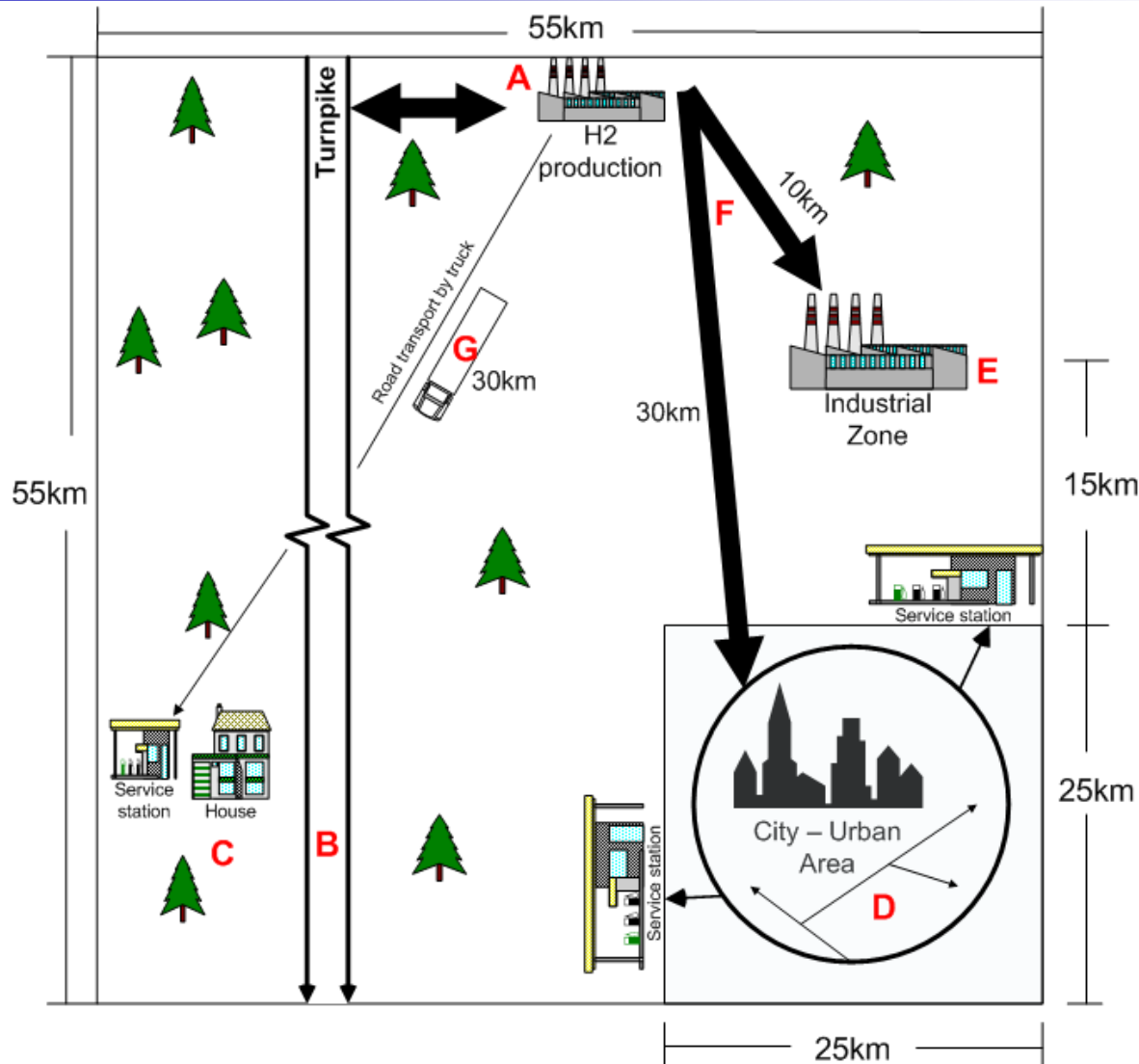
Hydrogen demand in EU-27 in 2050 Total: 49 Mtoe

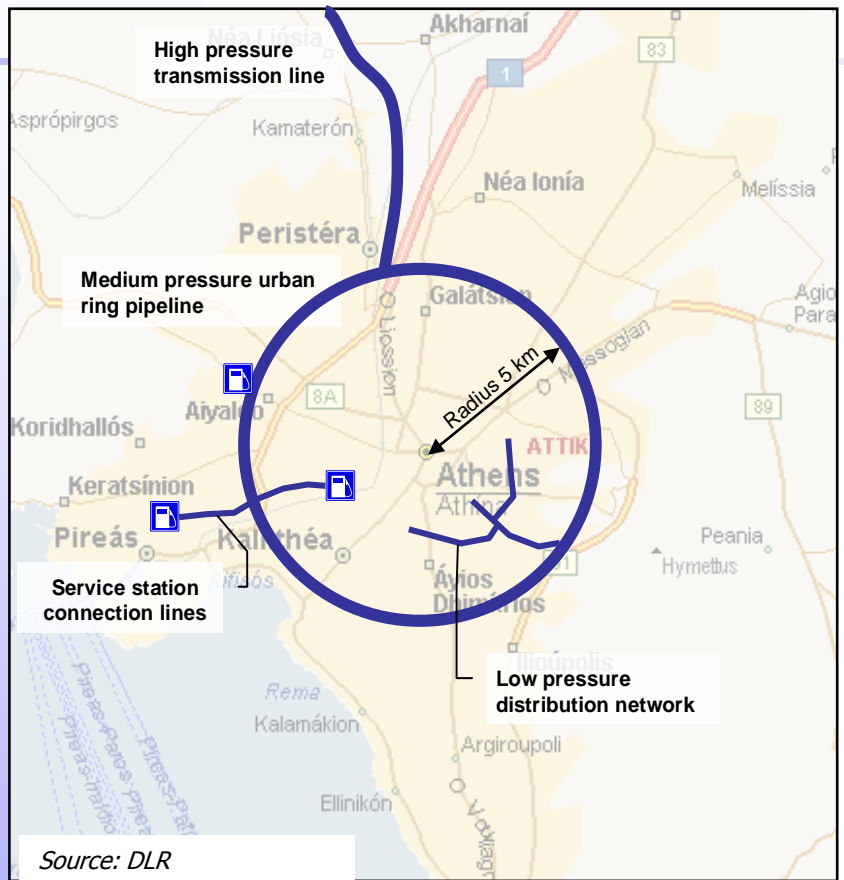


Source: PRIMES

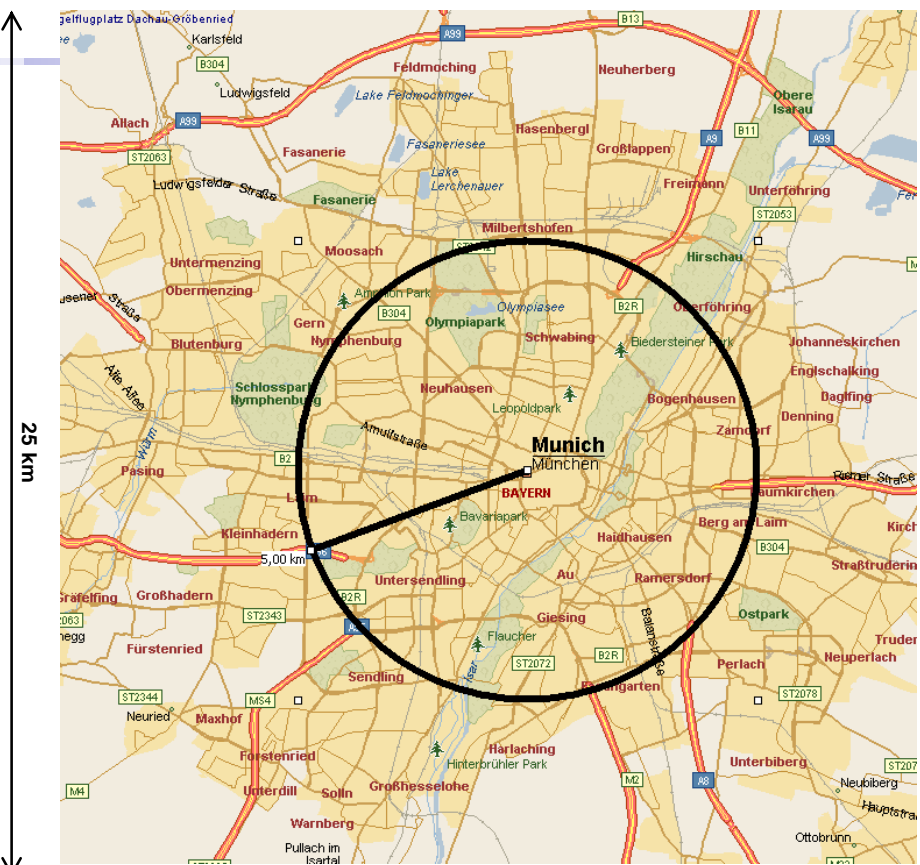
Reference infrastructure configuration

Early stages of take-off





25 km



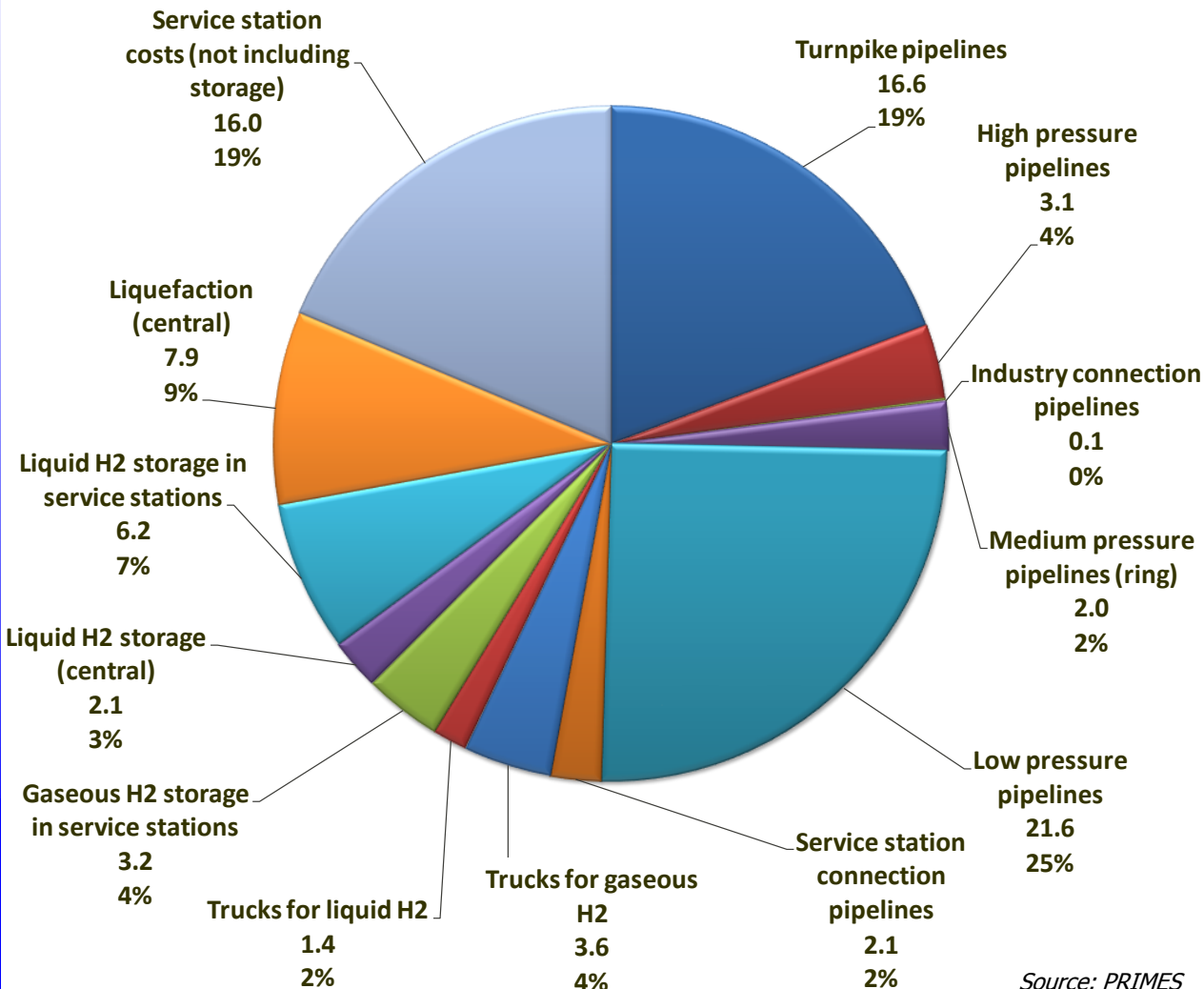
25 km

CASCADE

MINTS

Infrastructure investments

EU-27 cumulative 2005-2050 , total 89B€05



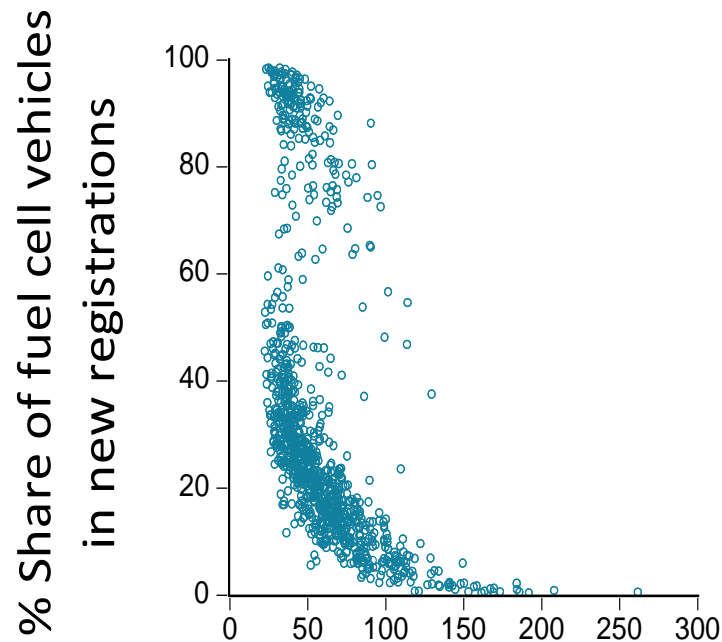
Pipelines	52%
Storage	14%
Trucks	6%
Liquefaction	9%
Specialised equipment *	11%

*compressors, dispensers, pumps

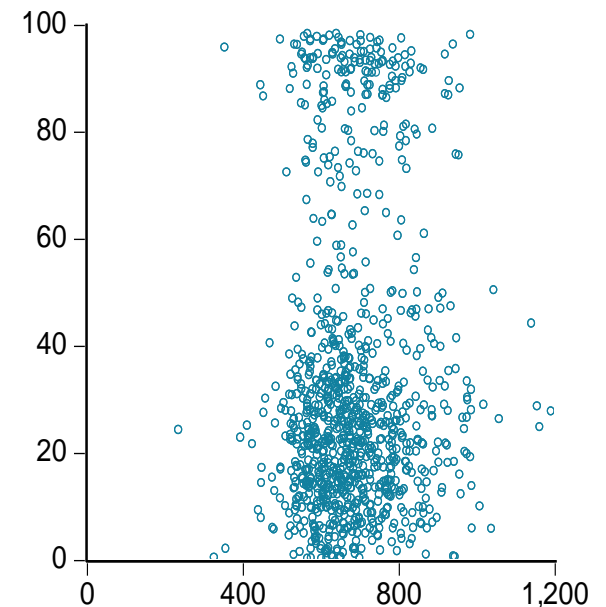
Source: PRIMES

Hydrogen costs and fuel cell penetration

Relative importance of hydrogen production cost variability for hydrogen penetration variability (Europe, 2050)



Fuel cell stack and system costs €05/Kw



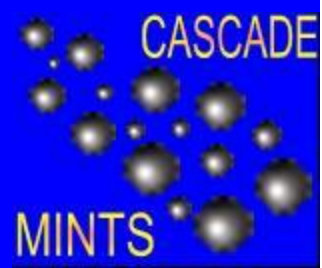
H2 delivered cost at the service station in €05/toe

Source: PROMETHEUS

Technical improvement and supportive policies

Scenario results for EU-27 in 2050

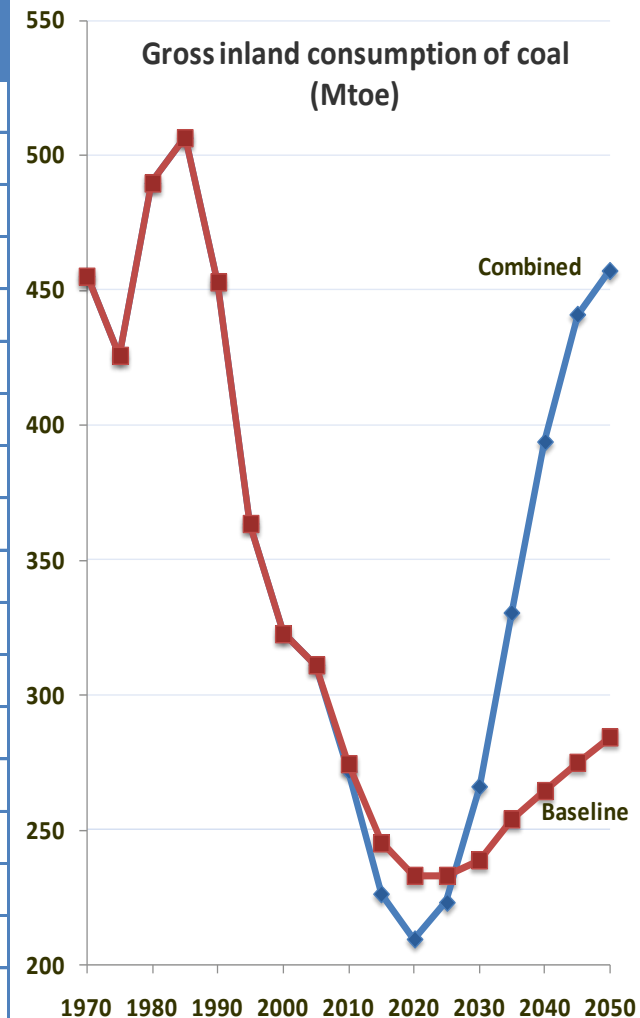
<i>Source: PRIMES</i>	% share in passenger cars stock						% in new car registrations	% share in final consumption of industry and residential/commercial		Hydrogen demand (Mtoe)
	<i>Conventional ICE</i>	<i>Hybrid</i>	<i>Plug in hybrid</i>	<i>Electric</i>	<i>H2 ICE</i>	<i>Fuel cells</i>	<i>Fuel cells</i>	<i>Electricity from fuel cells</i>	<i>Steam and heat from fuel cells</i>	
Baseline	64.1	11.1	4.7	1.7	5.2	13.3	24.8	2.2	3.7	49
Demand Pull										
FC	35.1	5.1	2.2	0.8	1.1	55.8	70.0	19.7	26.2	219
FC+TAX	29.5	3.7	2.0	0.9	1.3	62.6	76.9	19.0	25.1	215
FC+TAX+CV	28.1	3.3	2.0	1.0	1.3	64.3	79.0	24.1	31.6	281
Supply push										
H2P	63.5	10.9	4.7	1.6	5.4	13.9	25.6	3.9	6.6	67
H2P+INFR	61.6	10.5	4.5	1.6	7.1	14.8	27.1	10.4	18.2	150
H2P+INFR+CV	59.9	10.0	4.7	1.8	7.5	16.2	29.8	14.8	25.1	206
Combined case	28.0	3.3	1.9	1.0	1.4	64.5	79.1	27.2	34.6	314



- FC, H2P: Technologies reach their technical improvement potential in 2025
- TAX: 50 cents additional road fuel tax
- CV: Double baseline carbon value
- INFR: Free hydrogen distribution/storage infrastructure

Hydrogen production in EU-27 (2050)

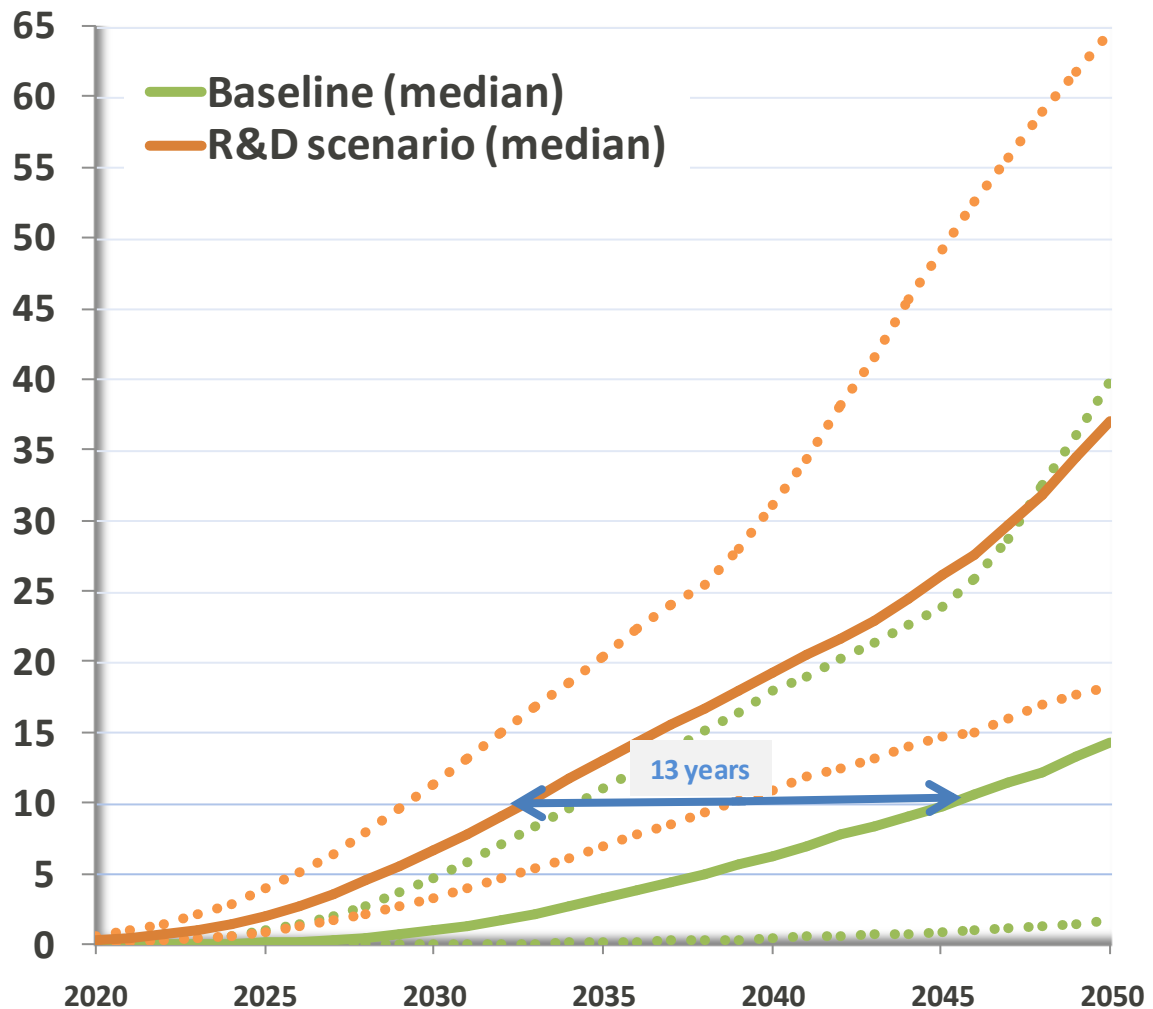
	% shares in production	
	Baseline	Combined
Fossil fuels without CCS	9.7	2.6
Gas steam reforming	8.3	1.9
Onsite	5.9	0.8
Centralised	2.4	1.1
Solar methane reforming	0.2	0.1
Coal gasification	0.2	0.0
Oil partial oxidation	1.1	0.6
Non Fossil fuels	19.8	27.5
Biomass pyrolysis	2.0	0.6
Biomass gasification with steam reforming	1.6	0.8
Nuclear high temperature therm. Cycle	8.5	17.6
Dedicated nuclear plant for electrolysis	6.4	6.7
Solar high temperature therm. Cycle	0.1	0.4
Electrolysis from grid	0.8	0.8
Dedicated wind turbine for electrolysis	0.4	0.6
Facilities with CCS	70.5	69.9
Gas steam reforming	0.4	0.4
Coal gasification	56.1	49.2
Oil partial oxidation	0.3	0.5
Biomass gasification with steam reforming	13.8	19.9



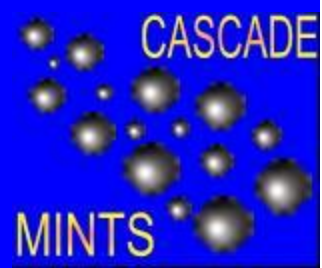
Source: PRIMES

Forcing the pace by additional R&D

% Share of fuel cell cars in vehicle parc in EU-27

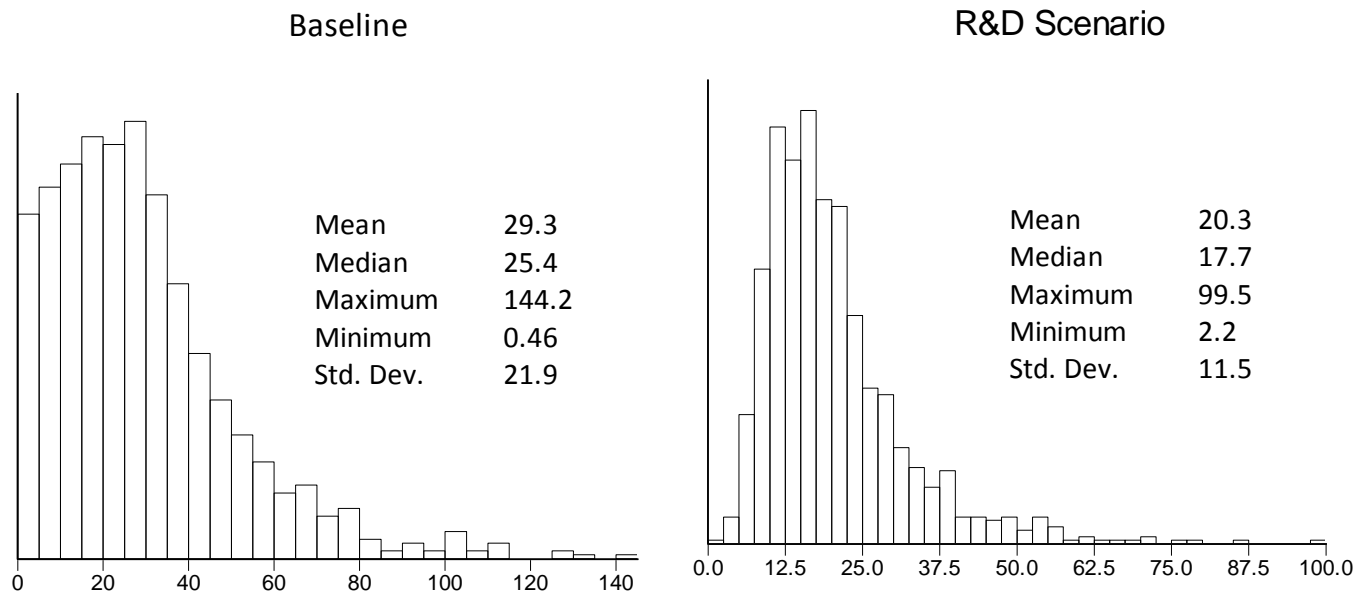


- Tenfold increase in R&D directed to fuel cells from 2007-2015 worldwide + 170 B€05



Effectiveness of additional R&D

Probability distribution of the ratio of discounted* technology sales and R&D expenditures



Source: PROMETHEUS

% Probability to fail reaching rate		
Rate	Baseline	R&D
6	11%	2%
10	18%	13%
60	91%	99%

* Discount rate: Real interest rate + 6%

A Valid Alternative Energy System

- A hydrogen based energy system does not pre-suppose a change in patterns of energy use
 - Small likelihood of social barriers
- Offers the best technical prospects for overcoming petroleum dominance of road transport
- Multiple potential applications in other sectors could create a snowball effect facilitating production capacity and infrastructure development
 - In such sectors though competition from a wider spectrum of alternatives can be expected

Consequences of eventual Success

A hydrogen based energy system

- Would not be less **energy intensive**
 - Gains in efficiency counterbalanced by transformation losses
- Would be **environmentally friendly**
 - Reducing local strains
 - But also compatible with global climate mitigation
 - Efficiency in final use combined with possibilities for very low carbon intensity in hydrogen production (e.g. CCS, Biomass)

Keys to success

- The improvement of technical and economic characteristics of **Fuel Cell** stacks and systems in mobile applications are an absolute **pre-requisite**
 - Stationary versions can improve as spin-offs
- The cost of producing hydrogen offers fewer prospects for reduction but is not an important consideration
- Storage, Transportation and Distribution infrastructure development will follow (with some lag) demand as long as it shows prospects of materialising on a sufficient scale

Slower than some expect

- Hydrogen in general and fuel cells in the key road transport sector are **unlikely** to:
 - Emerge before 2030
 - Gain significant shares (e.g. 10% of vehicle stock) before 2040
 - Be a dominant choice before 2050
 - Better prospects beyond
- Main reasons:
 - Still a long way to technical maturity
 - Inherently slow equipment turnover
 - Lags in infrastructure investment

Making it Happen

- Supportive policies (selective taxation and subsidies)
 - Inadequate in the absence of rapid technical progress
 - Unnecessary (and costly) in its presence
- Additional R&D for inducing technical change in demand technologies
 - Likely to accelerate developments
 - At the cost of lower expected RoR
 - But reduced risks of failure