UNIVERSITÀ DEGLI STUDI DI PADOVA

CENTRO GIORGIO LEVI CASES DI ECONOMIA E TECNICA DELL'ENERGIA

MOBILITÀ ELETTRICA
QUALE RUOLO PER L'IDROGENO?

MASSIMO GUARNIERI

Nuova Civiltà delle Macchine – Forlì
"Sviluppo Sostenibile. Verso l'Economia Circolare" 8-3-2021

Correva l'anno 2013 …

1959: Richard Feynman all'American Physical Society meeting

There's Plenty of Room at the Bottom

2013: C'è un sacco di energia lassù …..

→ I prossimi decenni vedranno il boom di nuove tecnologie energetiche

Car races, notably in France

18/12/1898: **Gaston de Chasseloup-Laubat** (1867-1903)
electric Jeantaud Duc: first official land speed record: 63.13 km/h
29/04/1999: **Camille Jenatzy** (1868-1913)
Jamais Contente: 105.88 km/h (first vehicle above 100 km/h)

France: largest automobile maker in the world up to 1904

01/05/1899 victory parade

Individual city cars

➔**Individual self-propelled cars used on urban streets**
➔**Electric cars ideal for wealthy city customers (status symbols)**
- John Davison Rockefeller's wife
- Henry Ford: three luxurious Detroit Electric

1906: Krieger electric landaulet owned by US senator George P. Wetmore

1904: Luxury electric landaulet in Berlin

American car maket

Around 1900

- **Steam cars – 40% of the car market**
  well established technology, powerful, fast, and reliable, ….
  But: long start-up times (25-45 min), short range (water refilling), skilled operators needed

- **Gasoline cars – 22% of the car market**
  noisy, smelly, unreliable, heavily vibrating, problematic gear changes, difficult and dangerous to crank-start, strong operators needed

- **Electric cars – 38% of the car market**
  silent, odorless, reliable, simple to drive, and easy to start ("women's cars"),
  But: expensive, slow (24-32 km/h), low ranging (30-60 km), long recharge (hours)

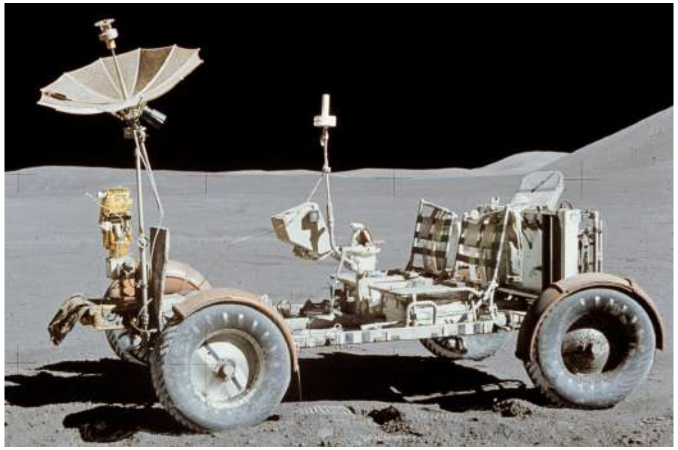
  1900-1910 peak of electric cars

1910-1990: quiescence decades

Niche use: golf carts, milk vans, post vans, forklifts, NEVs

1953: East German post vans

1960: US Henney Kilowatt



1971: Moon Rover (Apollo 15)

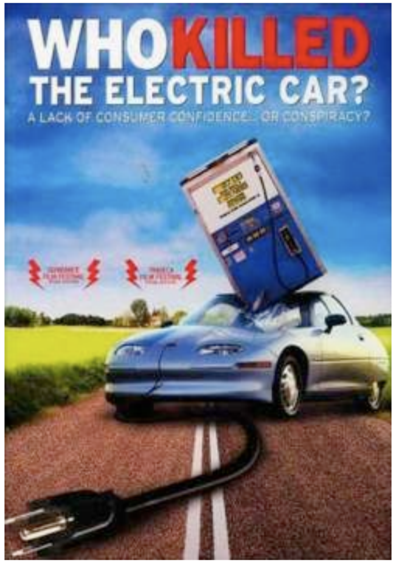
After 1990: new motivations

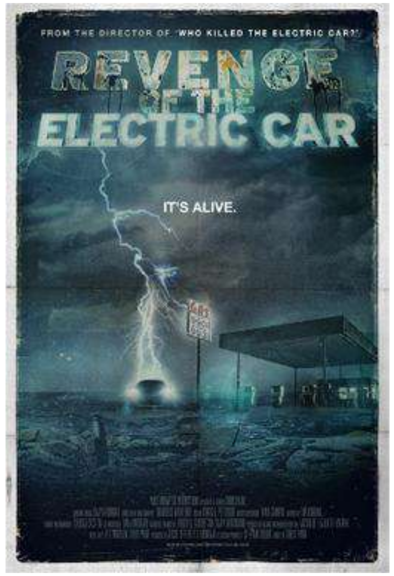
1990: California Air Resources Board's (CARB) mandate for low-emission vehicles
→ New EVs by Chrysler, Ford, GM, Honda, Nissan, Toyota

1996-1999: GM EV1 first mass-produced EV
102 kW, 26.4 kWh Ni-MH (later version)

1999: CARB's mandate withdrawn,
EV discontinued
Economic interests of car manufactures

2006 movie: Who Killed the Electric Car?



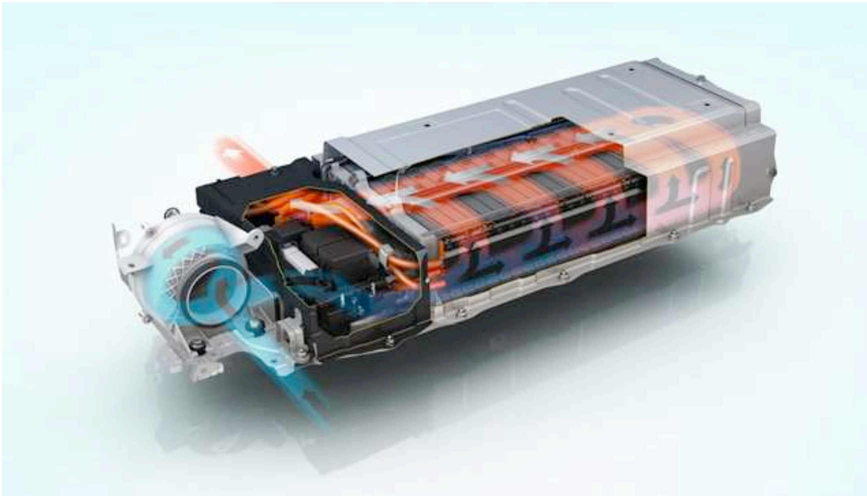


2011 movie: Who Saved the Electric Car?
and oil industry (Revenge of the Electric car)

>2000: HEVs

Hybrid Electric Vehicle
ICE (prevalente) + EM (frenata rigenerativa) →
riduzione consumi, riduzione emissioni, maggior efficienza, maggior autonomia

model	year	ICE [kW]	EM [kW]	battery	batt. [kWh]	sales
Toyota Prius	1997 2003	73 73	60 60	(1^ gen) NiMH (2^ gen) NiMH	1.78 1.31	1^–4^ gen 6.1x10^6 (01/2017)
Honda Civic IMA	2003	70	15	NiMH	0.8	
Ford Fusion Hybrid	2009	116	79	NiMH → Li-ion	1.4	
Ford C-Max Hybrid	2012	78	62	Li-ion	1.4	
…….						



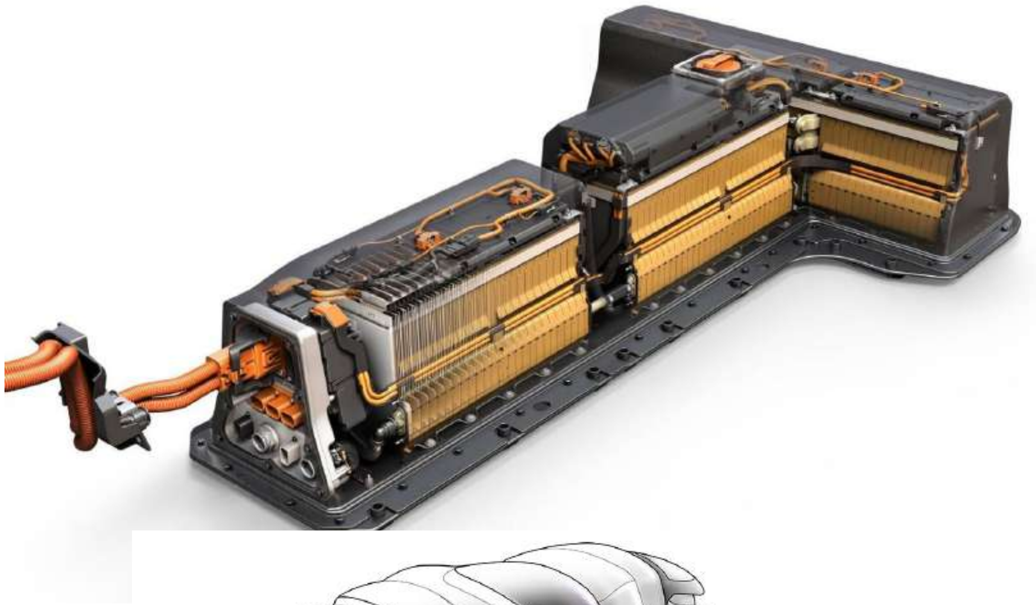
>2010: PHEVs

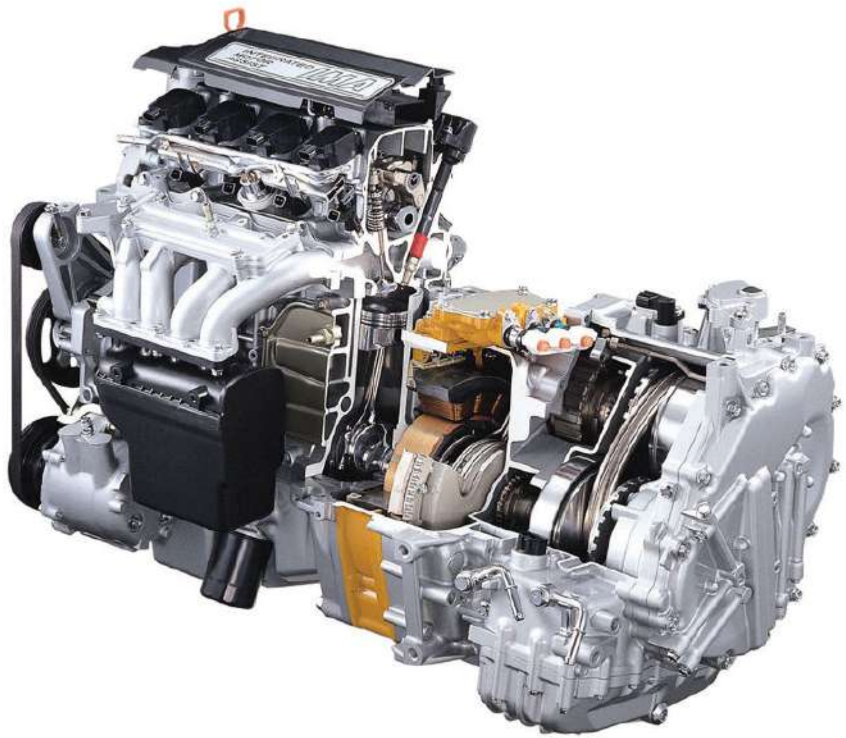
Plug-in Hybrid Electric Vehicle

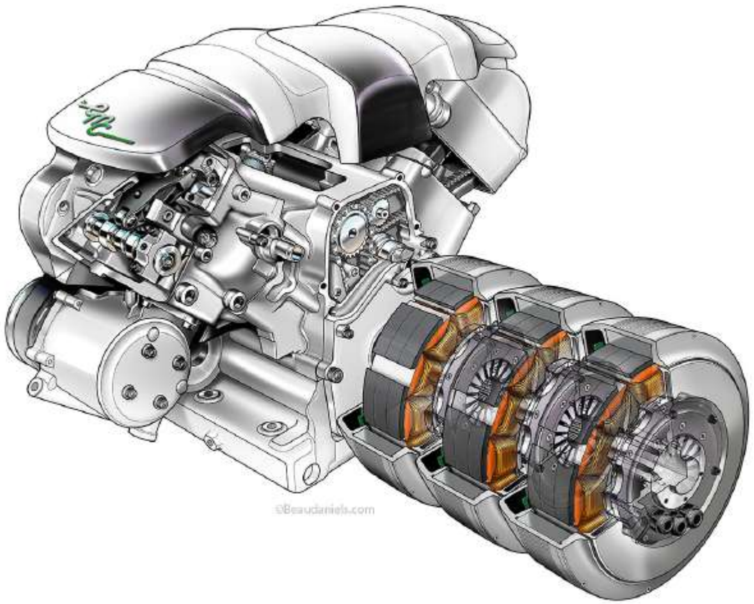
Ricarica da ICE ed esterna = maggiore autonomia, no range anxiety (partial list)

model	year	ICE [kW]	EM [kW]	battery	batt. [kWh]	range [km]	sales
Chevrolet Volt (GM) Opel Ampera (GM)	2010	63	111	Li-ion	16.0	56	87×10^3(11/2014)
Volvo V60 Plug-in Hybrid	2011	171	51	Li-ion	12.0	50	
Toyota Prius Plug-in Hybrid	2012	73	60	Li-ion	4.4	23	
	2016	73	60	Li-ion	8.8	40	
Mitsubishi Outlander P-HEV	2012	102	120	Li-ion	12.0	60	
Ford Fusion Energi	2013	105	88	Li-ion	7.6	34	
Honda Accord Plug-in Hybrid	2013	129	120	Li-ion	6.7	21	
McLaren P1	2013	542	132	Li-ion	4.7	10	

>2010: PHEVs







>2007: BEVs

Battery Electric Vehicles - Mostly city cars (partial list)

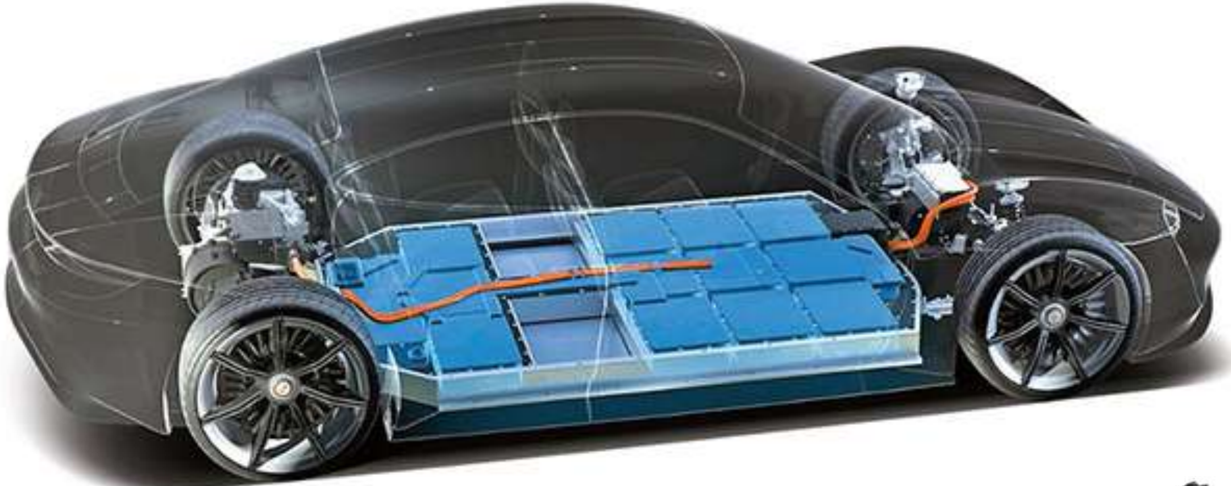
model	N	year	EM [kW]	battery	batt. [kWh]	range [km]	sales/note
Smart ED	D	2007	20	Li-ion	16.5	135	
Mitsubishi i MiEV	J	2009	47	Li-ion	16	160	
Volkswagen e-Up!	D	2009	60	Li-ion	18	130	
Nissan Leaf	J	2010	80	Li-ion	24	175	4×10^5 (03/2018)
BYD e6	PRC	2010	75 200	$LiFePO_4$ $LiFePO_4$	61 80	300 400	4000 cycles 10 years
JAC J3 EV	PRC	2010			130		
Ford Focus Electric	US	2011	107	Li-ion	23-33	122-185	
Bolloré Bluecar	F	2011	50	Li-pol	30	250	
Renault Fluence Z.E.	F	2011	70	Li-ion	22	185	
Renault Zoe	F	2012	65	Li-ion	22	210	
Honda Fit EV	J	2012	92	Li-ion	20	140	
Toyota RAV4 EV 2^ gen	J	2012	115	Li-ion	41.8	166	
Roewe E50	PRC	2012	47	$LiFePO_4$	18	180	
Mahindra e2o	IN	2013		Li-ion	16	120	
Chevrolet Spark EV	US	2013	97	Li-ion	21.3	132	
Fiat 500	US	2013	83	Li-ion	24	140	
BMW i3	D	2014	125	Li-ion	19	190	
Kia Soul EV	KR	2014	81	Li-ion	27	200	
Chery QQ3 EV 2^ gen	PRC	2014	42	Li-ion		200	US$9600

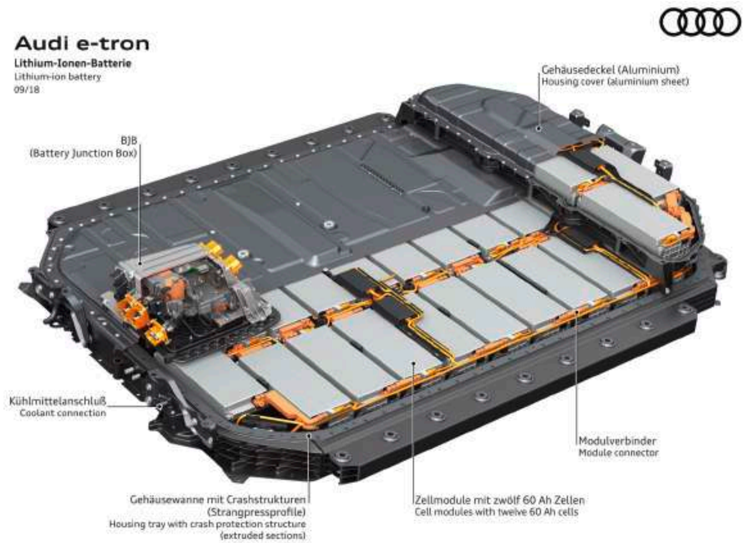
>2008: super BEVs

High-level Battery Electric Vehicles (partial list)

model	year	EM [kW]	battery	batt. [kWh]	range [km]
Tesla Roadster	2008	185-215	Li-ion	53	393
Tesla Model S	≥2012	≤615	Li-ion	100	560-647
Tesla Model X	2015	≤568	Li-ion	100	523
Tesla Model 3	2017	307	Li-ion	82	568
Jaguar i-pace	2018	290	Li-ion	90	470
Porsche Tycan	2019	≤560	Li-ion	93.4	463
Audi e-tron GT	2020	475	Li-ion	93.4	425

Electric cars (EV)



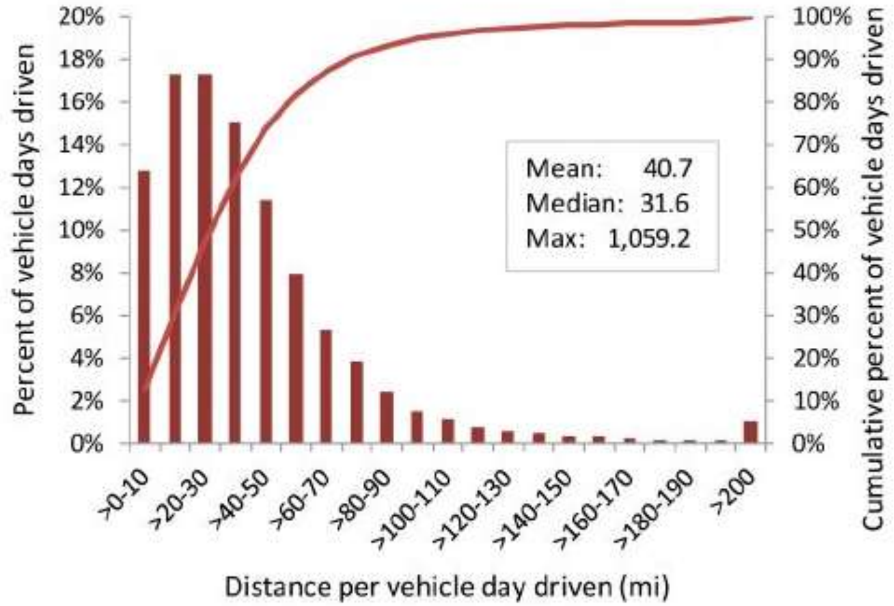


Accumulatori

<65 km/dì: 68% degli autisti

65<X<160 km/dì: 25% degli autisti

>160 km/dì: 7% degli autisti



Aumento dell'autonomia

Riduzione dei tempi di ricarica

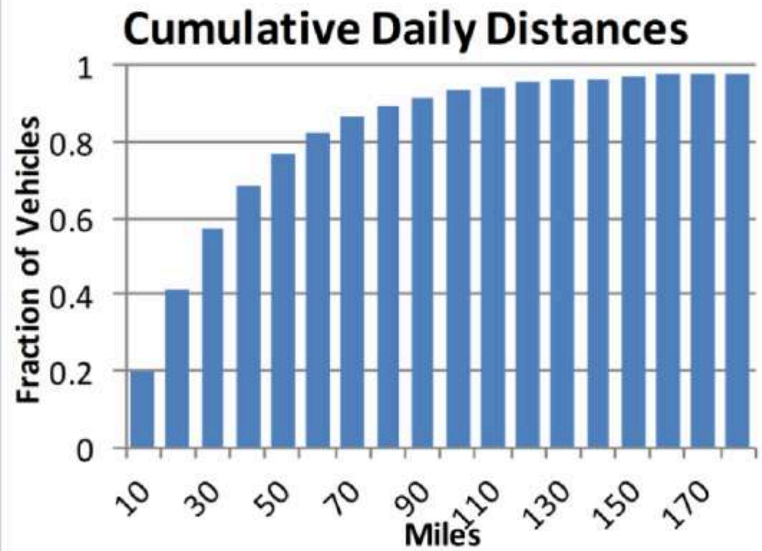
10 h a 3 kW → 15 min a 120 kW

Riduzione del costo

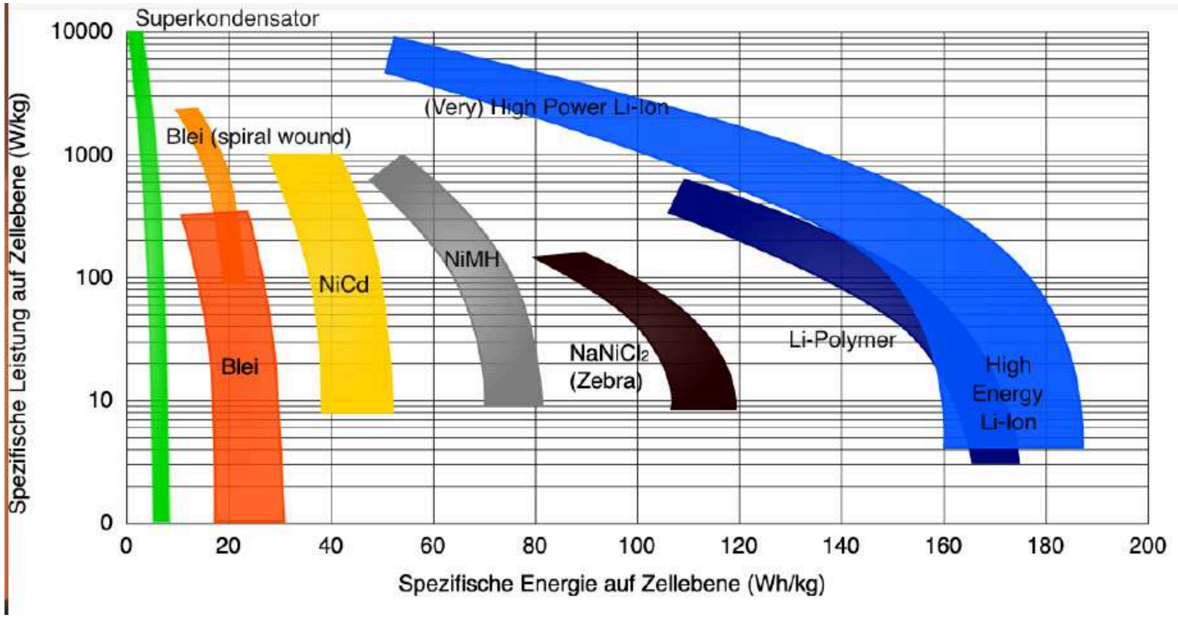
140 €/kWh (1/8 che nel 2010)

Aumento dei cicli di vita

5.000 → 15.000

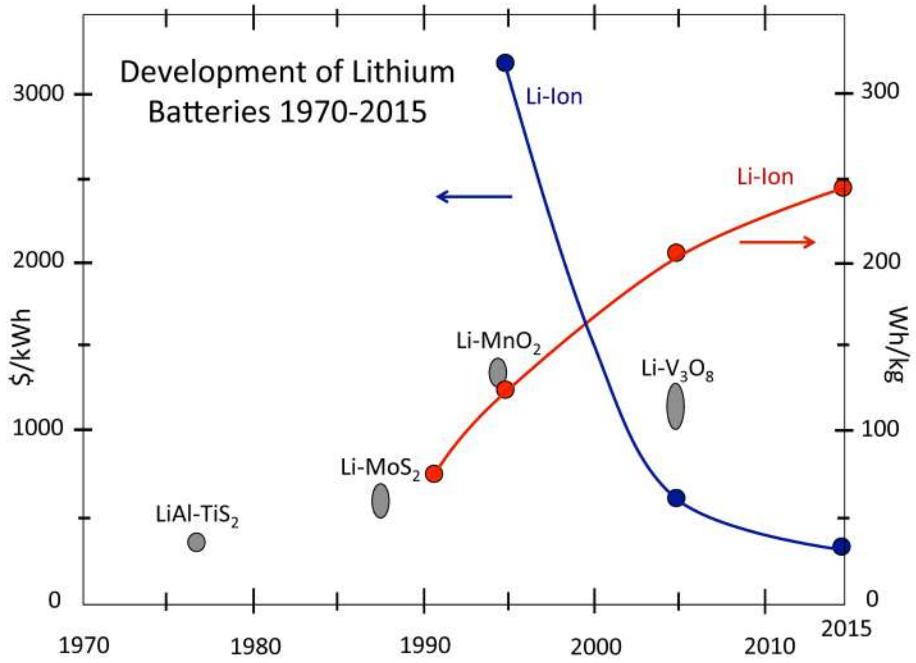


Chimiche diverse per batterie

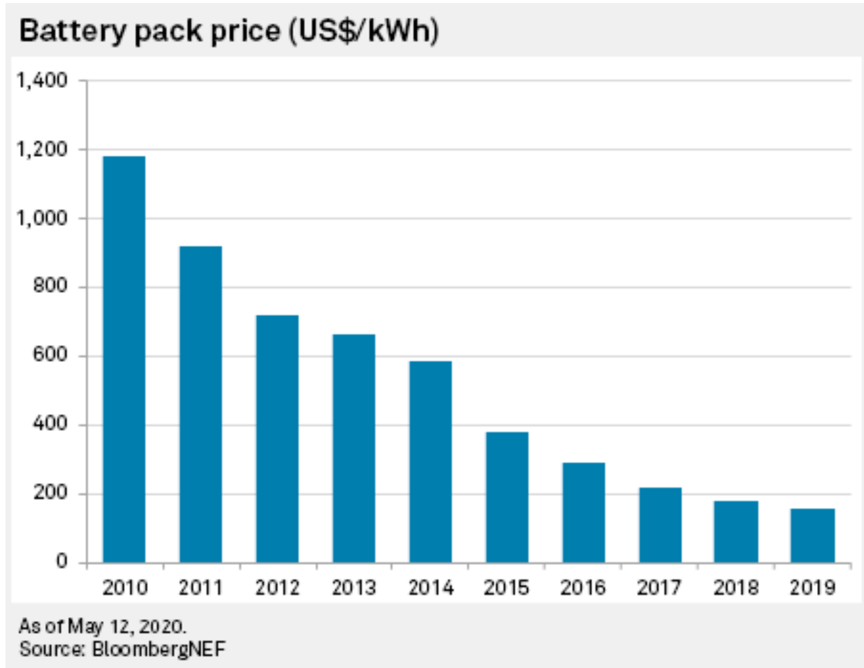


Battery type	Pb	Ni-Cd	Ni-MeH	Na-S/Na-NiCl$_2$	Li-ion
Energy density vol. [Wh/L]	90	150	200	345/190	300-400
Energy density grav. [Wh/kg]	35	50	70	170/120	200-300
Power density vol. [W/L]	910	2000	3000	270	4200-5500
Power density grav. [W/kg]	430	700	1200	180	3000-3800
Self-discharge	+	+	+	-	++
Fast charging	--	++	+	-	+

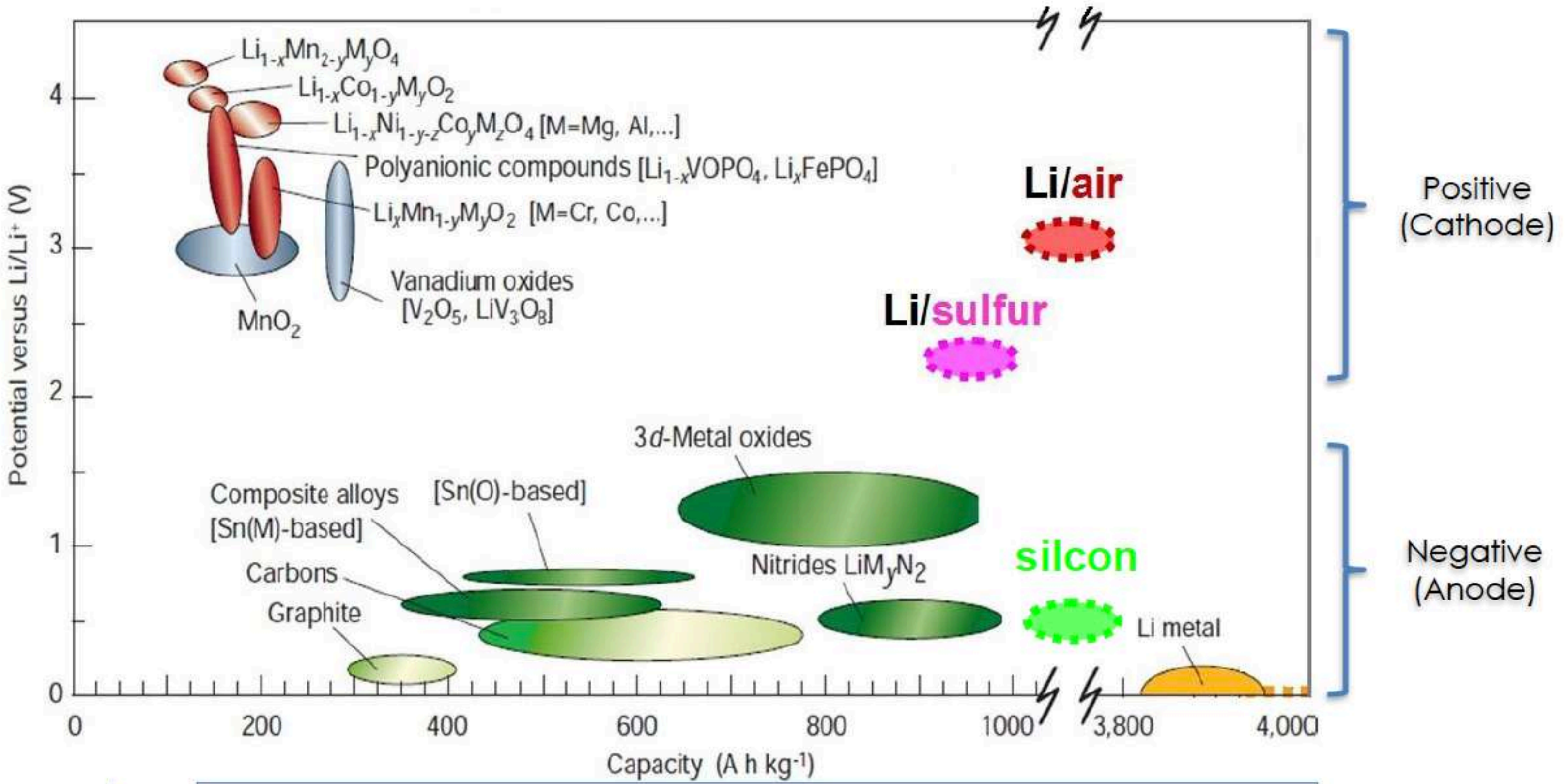
litio: evoluzioni incrementali



Crabtree, Kocs, Trahey, MRS Bulletin, Dec 2015



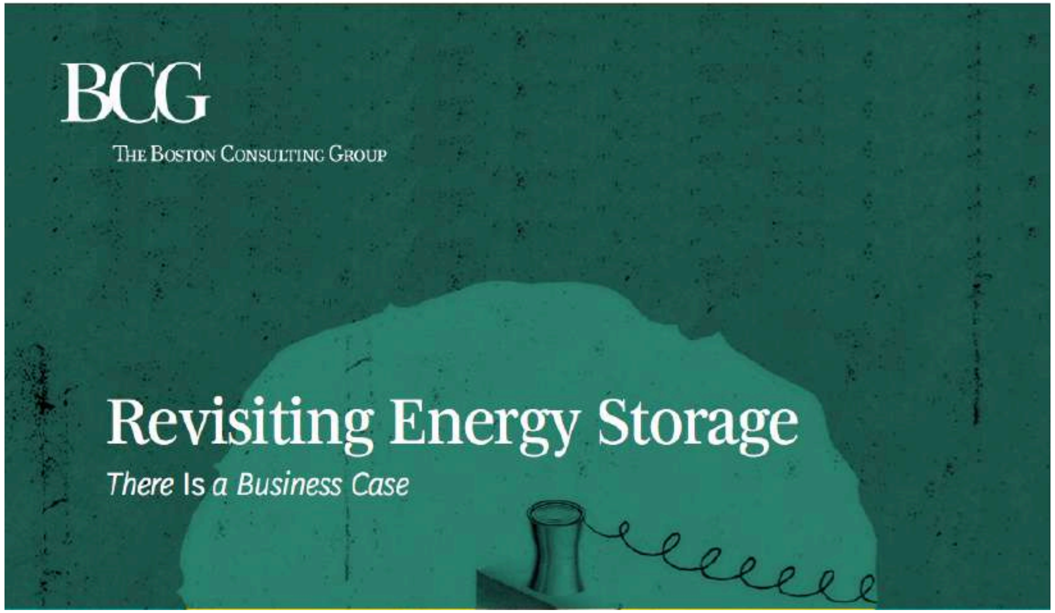
Ora: diverse chimiche del litio – metalli diversi accoppiati al litio al catodo
Futuro: beyond lithium



Compound formation / alloying rather than **intercalation** in host structure

Post Li-ion batteries: Li-air and Li-S batteries with Si or Li anodes

Energy Storage Market



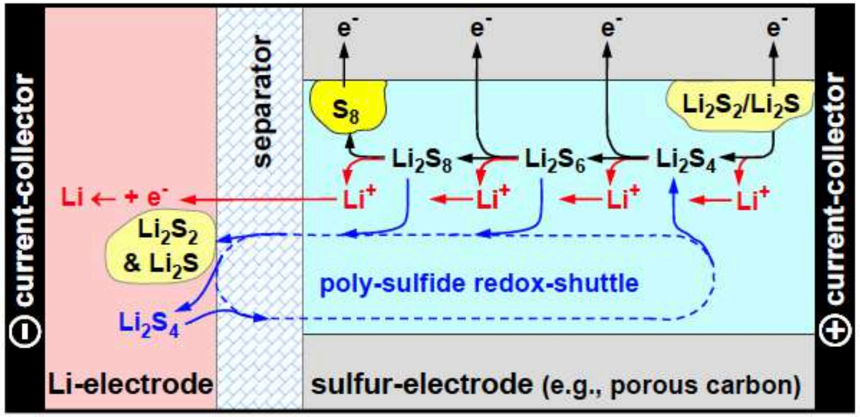
2011 Forecast
Boston Consulting Group
gradual increase to
2020: US$ 10 billion/year
2030: US$ 280 billion investments
330 GW (250÷300% of 128 GW in 2011)
n.b.: 193 GW as of today (source DOE)

C. Pieper, H. Rubel, “Revisiting energy storage. There is a business case,” Boston Consulting Group Report, Feb. 2011

Future Concepts – Li-S Batteries

Concept

$$S + 2\,Li^+ + 2\,e^- \leftrightarrow (Li_2S)_{solid} \quad \text{(cathode)}$$
$$2\,Li \leftrightarrow 2\,Li^+ + 2\,e^- \quad \text{(anode)}$$
$$2\,Li + S \leftrightarrow (Li_2S)_{solid}\,;\ \Delta U_0 \approx 2.0\ V$$



Challenges and R&D needs

- Polysulfide diffusion to anode ⇒ Li^+-conducting diffusion barrier
- Poor C-rate & cathode "clogging" ⇒ Cathode design
- Stable anode configuration ⇒ Improved Li-metal anode design or alternative

Advantages

- High specific capacity: 630 $Ah/kg_{electrode}$
- High energy density: **950 $Wh/kg_{electrode}$**
- Low cost of sulfur
- Minimal degradation during charge cycling

Gain vs. state-of-the-art batteries: 2-fold

Novel Concept: Magnesium Batteries

Novel Concept – F-ion Batteries

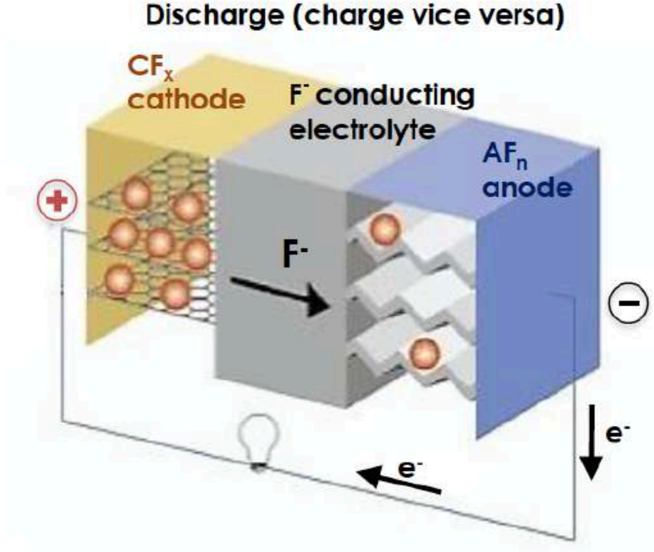
Concept

Reminder: Li-ion reaction

$$LiC_6 + 2Li_{0.5}CoO_2 \leftrightarrow 2LiCoO_2 + 6C \; ; \; \Delta U_0 \approx 4.1 \text{ V}$$

F-ion reaction

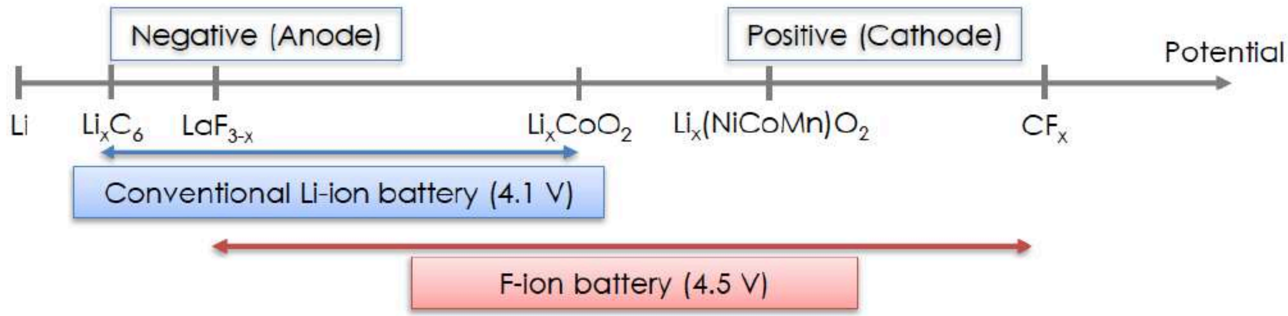
$$LaF_3 + 3CF_y \leftrightarrow LaF_{3(1-x)} + 3CF_{x+y} \; ; \; \Delta U_0 \approx 4.5 \text{ V}$$



Advantages

- High theoretical energy density: **1560 Wh/kg**
- No need for scarce elemental lithium
- **Safer** than Li-ion batteries (no oxygen present)

Choice of redox couple

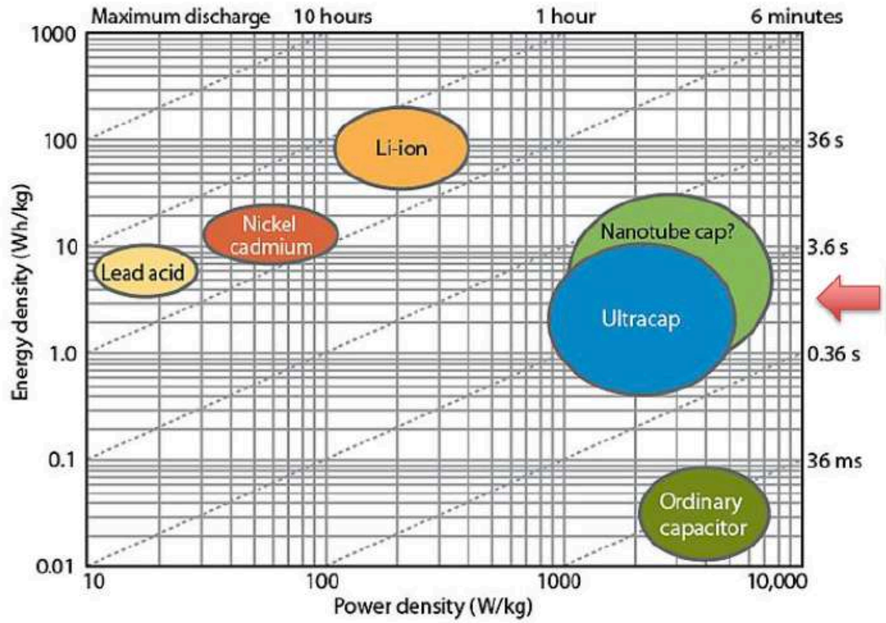


SCES (Supecapactor Electric Energy Storage)

Supercondensatori

Single unità:

•10^0 V
•10^3 F
•Carica e scarica molto rapide
•Lunghissima vita (10^6 cicli)
•Assemblabili in banchi s/p
e.g.: 120 V - 63 F - 126 (105) Wh



Impieghi:

Mobilità

- Capabus (EXPO 2010) → ?
- propulsione ibrida → !

Tecnologie emergenti:

- Gestione sequenziale dei pacchi di batterie
- Fast recharge: elevata potenza alla colonnina 150 kW – 250 kW
- Battery swap (fast exchange)
- Range extender con ICE ottimizzati

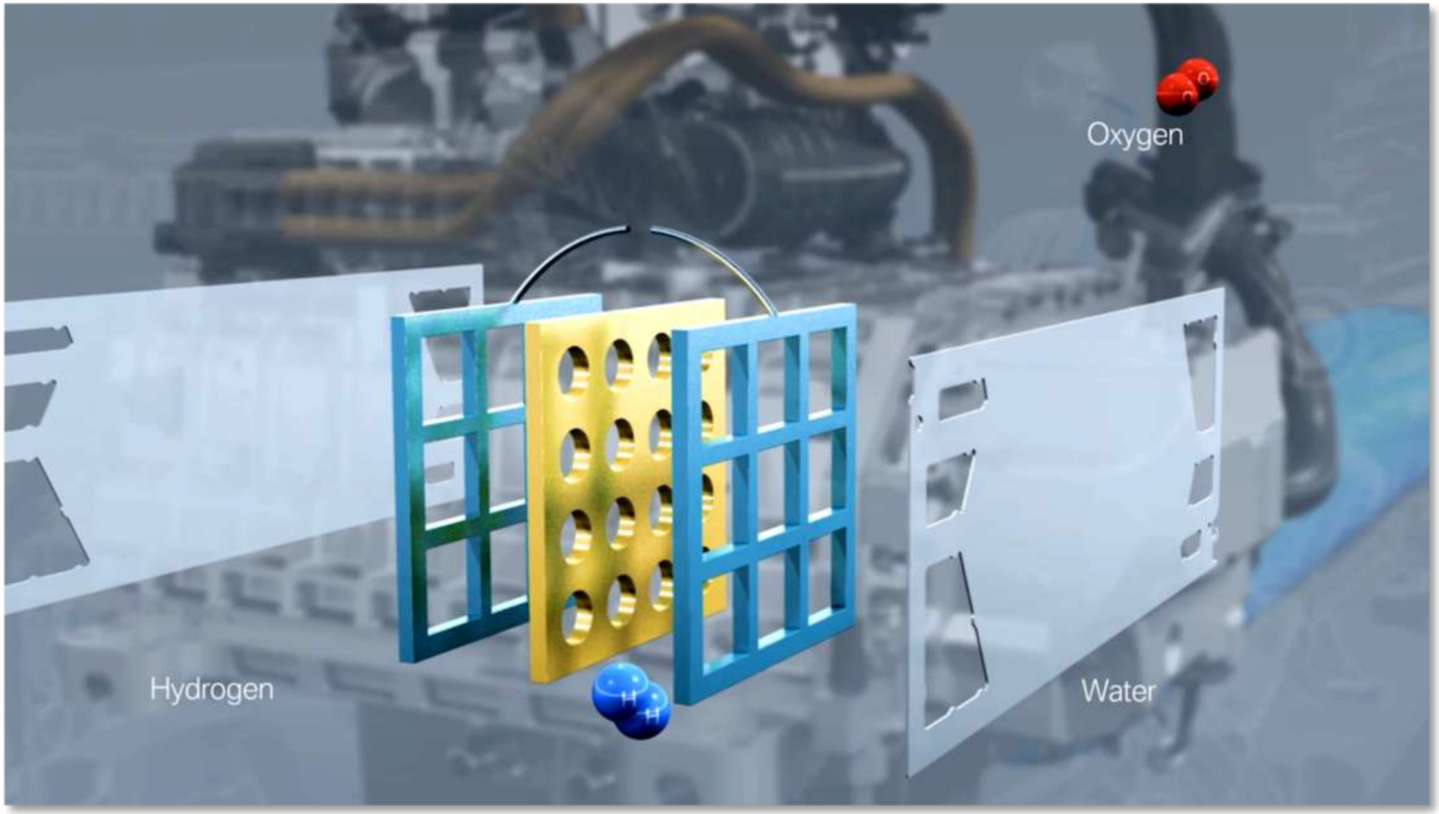
BMW i3 range extender (2014): 125 kW - 19 kWh Li-ion
+ 26 kW – 9 L – 340 km

ICE avanzati a turbina

Fuel Cell – Cella a Combustibile

come funziona:

usa **idrogeno** (=combustibile) + ossigeno (atmosferico)
per produrre **energia elettrica** ed acqua distillata



H2 + Fuel Cell

H_2 high energy density — DOE Targets

3 kWh/kg — 2.7 kWh/L $2/kWh

storage > 100L @ 70MPa in compact volumes

PEMFC

low temperature (90 °C)

precious cathayzers (cost, H2 purity) — DOE Targets

high power density: 2.5 kW/L — 3 kW/L (→2035)

η = 45%

→ fair dynamics

$75/kW, 4000 h — $30/kW (2050), 8000 h (2050)

SOFC/MCFC

high temperature (300-500 °C)

η = 55-65%

→ slow dynamics

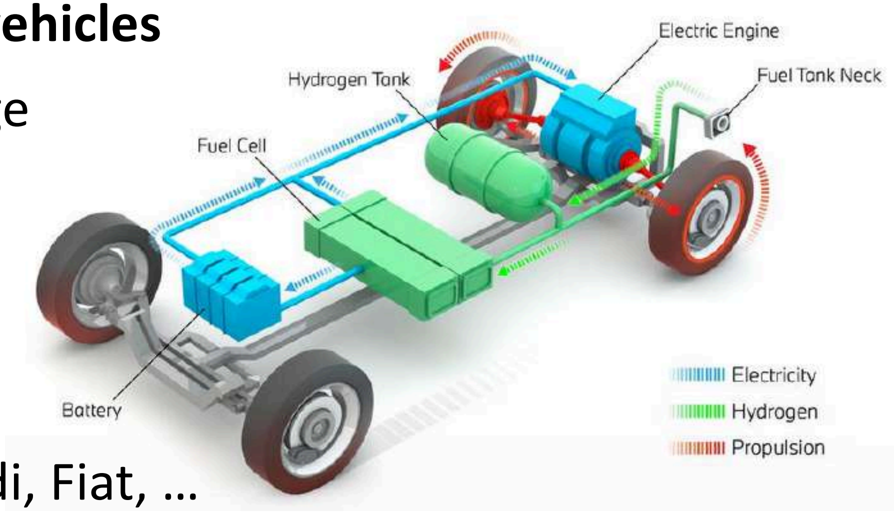
→ high temperature exhaust gases (CHP)

FCEV – HFCEV: Fuel-cell powered electric vehicles

Tank with hydrogen (70 MPa) = energy storage

Fuel cell H2 fed = electricity generation

Electric motor = propulsion



1999-2010: Several prototypes

Lotus, Ford, Mercedes, Nissan, BMW, GM, Audi, Fiat, …

Pre-series - limited production (partial list)

2001: Hyundai Santa Fe

2002: Toyota FCHV

power: FC 90 kW + NiMH 21 kW

energy: H2 156 L @ 70 MPa → **800 km**

2008: Honda FCX Clarity

100 kW FC + Li-ion @ 35 MPa → 380 km

….

FCEV – HFCEV: Mass production

year	model	FC [kW]	Li-ion [kW]	speed [km/h]	Li-ion [kWh]	H2 [kg]	p_{H2} [Mpa]	range [km]
2013	Hyundai ix35 (Tucson)	100	24	160	0.95	5.64	70	594
2015	Toyota Mirai FCV (2^g)	130	21	178	1.6	5.0	70	528
2016	Honda FCX Clarity II (2^g)	103	si	160	si	3.9	70	589
2018	Hyundai Nexo	120	21	171	1.6	6.3	70	611
2019	Mercedes GLC F-Cell	160	18	160	13.5	4.4	70	478

Hyundai ix35 (Tucson):

refueling time: 3 min

Toyota Mirai FCV (2^g):

FC: 3.0 kW/L !! (58.5 k$ → 49.5 k$)

Sells 12/2019: 10250 units
US: 6200
Japan: 3500
Europe: 640

FCEV – HFCEV: Europe

2020: European development programs:

- Mercedez,
- BMW → on sale in 2022
- Audi, …

ma con qualche problema evolutivo …

Electrek Apr 22, 2020: “**Daimler** ends hydrogen car development because it’s too costy”

Wardauto Mar 02, 2021: “**Audi** renews hydrogen Fuel Cell development”

Two competing concepts

BEV:
Tesla Model 3

- 307 kW
- 82 kWh
- 568 km
- 250 km/h
- 0-100 km/h 3,7 s
- 48 k€
- recharging time: 27 h @ 3 kW
  41 min @ 120 kW

FCEV:
Toyota Mirai

- 136 kW
- H2: 122.4 L @ 70 Mpa, 5.0 kg
- 528 km
- 178 km/h
- 0-100 km/h 9.6 s
- 49 k€
- refuelling time: < 5 mins

n.b.: gasoline/diesel refuelling power = 15-20 MW

H2-FC

Independent
energy (tanks) / power (FC) sizing
→ Long service

Producers

Mercedes-Benz, MAN, Solaris, VanHool, VDL

Typical specifications:
motors: 150 (300) kW
power supply: 150 kW FC + 100 kW Li-ion
energy: H2 1,640 L @ 35/70 MPa + 17.4 kWh Li-ion
in 8 Dynetek carbonfiber reinforced aluminum tanks (35 kg)

EU (FCH-JU) Funded programs: High V.LO City – IFC – CHIC

Urban public transportation

- London, Hamburg, Köln, Aargau, Aberdeen, Oslo, Barcelona, Stuttgart, Amsterdam, Luxemburg, Madrid, Reykjavík, **Bolzano**, Ventimiglia, Milano, …
- non-EU programs: Vancouver, Whistler, Perth, …

Italian cases:

- Bolzano: project CHIC, 5 autobus Mercedes Citaro FuelCell Hybrid + refueling station (operating!)

- Taggia-Ventimiglia: High V.LO City program A330 Van Hool 450 km (refuel < 15 min) (refueling station? → salvataggio regionale)

- Val di Fiemme: Dolomitech 2 minibus Daily modificati 300 km (refueling < 10 min) dismissed reactivated for Winter Olympics 2021

Coradia iLint
Fuel cell & H_2 train

→ Producer
→ **Alstom (F / D)**
2 x 390kW
140 km/h, 130 seats

Regional transportation
2018: in service (D, DK, NL, CAN, …)

Competitiveness
vs Diesel trains
(emissions, efficiency, noise, …)
vs pure electric & electrical lines?
(to be assessed: line extension, number of of trains, on board generators, **H_2 production/supply**, …)

Waterborne FCEV

Prototype FC–H_2 boats

2009 Amsterdam

H2 Nemo

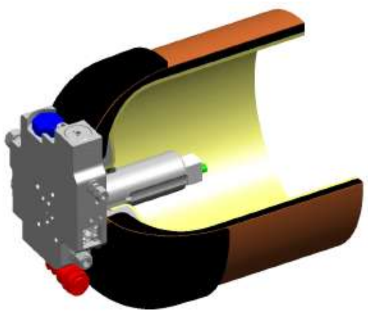
- 22 m - 87 passengers
- "zero CO_2 canal cruise"
- 75+11 kW propulsion
- 70 kW FC – 50 kW battery
- 6 tanks – 24 kg @ 35 MPa
- 8.6-7 knots – 9 h

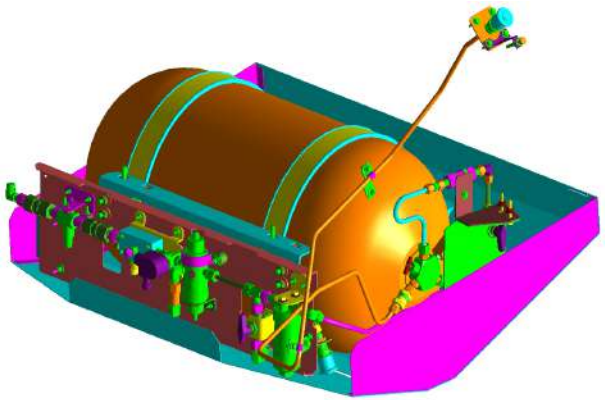
Similar FC boats:

- Alsterwasser (Hamburg), Berlin, Bristol, La Rochelle, Rotterdam, New York, Istanbul, …
- Venice … ?

On board storing
HP now a safe tecnology

- 70 (35) MPa – composite materials (Kevlar)



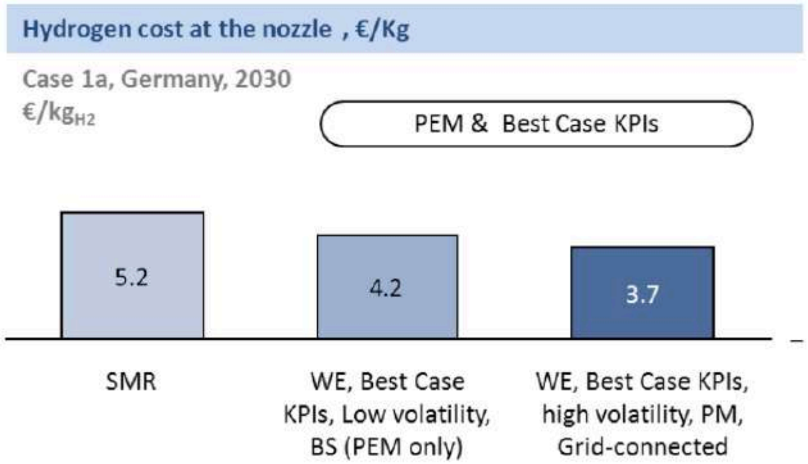


Validation tests:

- Hydrostatic Burst
- Extreme Temperature Cycle
- Ambient Cycle
- Acid Environment
- Bonfire
- Gunfire Penetration
- Flaw Tolerance
- Accelerated Stress
- Drop Test
- Permeation
- Hydrogen Cycle
- Softening Temperature
- Tensile Properties
- Resin Shear
- Boss End Material

Refueling infrastructure - HRS

- Methane reforming
- RES supply + **electrolyzer**
- mid pressure + compressor
- 0.5 – 1 M€ each



		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm^3_{H2}/h	0.25 – 760	0.01 – 240	0.1 – 1
	kW	1.8 – 5,300	0.2 - 1,150	0.7 – 4.5
Hydrogen purity [6]		99.5% – 99.9998%	99.9% – 99.9999%	99.4%
Indicative system cost	€/kW	1,000-1,200	1,900 – 2,300	N/A

PEM = proton exchange membrane
AEM = anion exchange membrane

Refueling infrastructure – HRS

Comparison H2 - Gasoline - Diesel fuel – Futuristic pictures

		H2 (1 bar)	H2 (690 bar)	Gasoline	Gasoline DI	Diesel Fuel TDI
specific energy	MJ/kg	141,86	141,86	46,4	46,4	45,6
energy density	MJ/L	0,01005	4,5	34,2	34,2	38,6
density	kg/L	7,08E-05	3,17E-02	0,74	0,74	0,85
price	€/L			1,57	1,57	1,49
price	€/kg	4,95*	4,95*	2,13	2,13	1,76
fuel energy price	c€/MJ	3,49	3,49	4,59	4,59	3,86
powerdrive efficiency at the wheel	%	*60%*	*60%*	26%	*34%*	*45%*
wheel energy price	c€/MJ	5,82	5,82	17,66	13,50	8,58

*at present 13.7 /kg

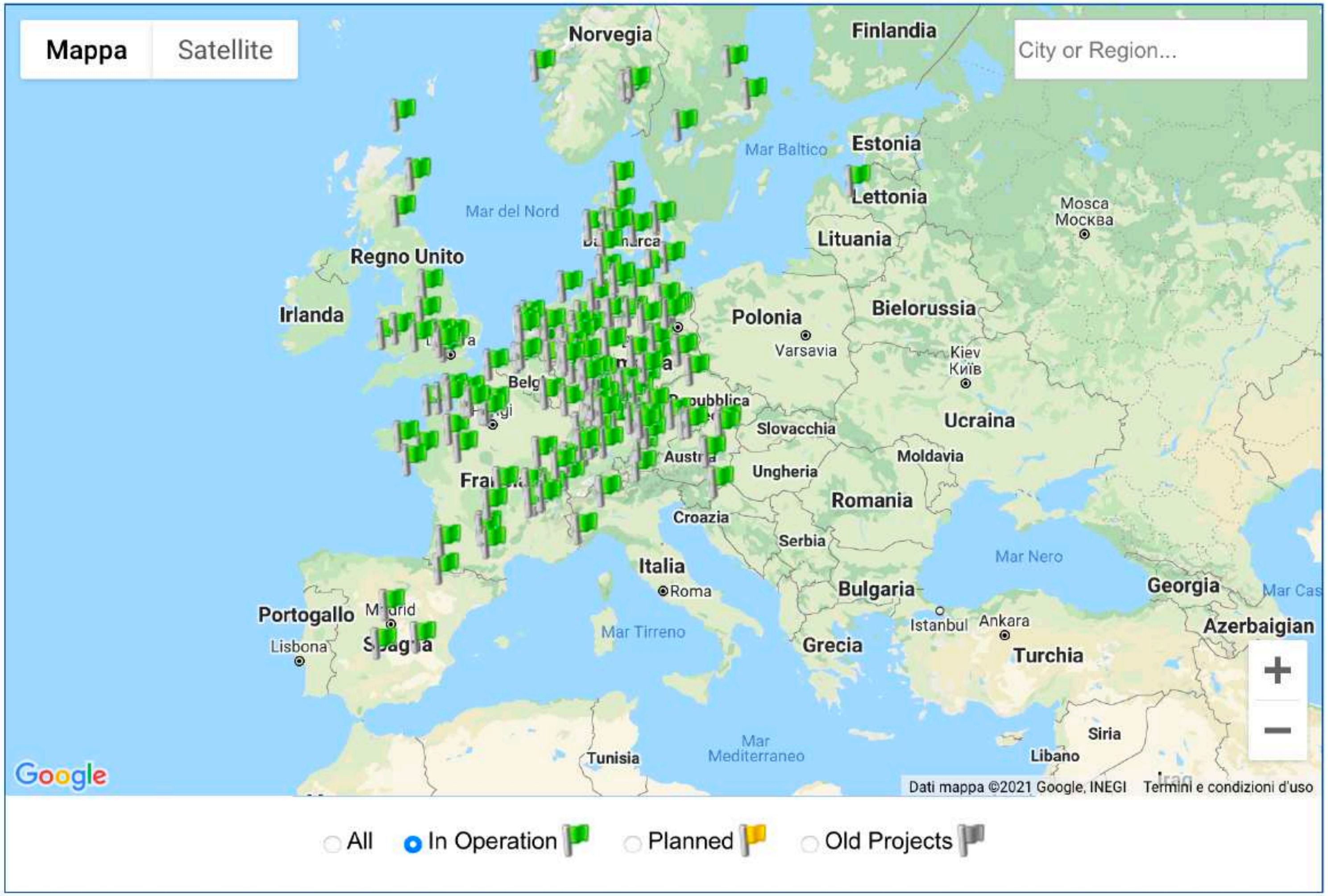
Italic efficiencies: optimistic values, future targets

Refueling infrastructure
EU and national regulations
January 2017

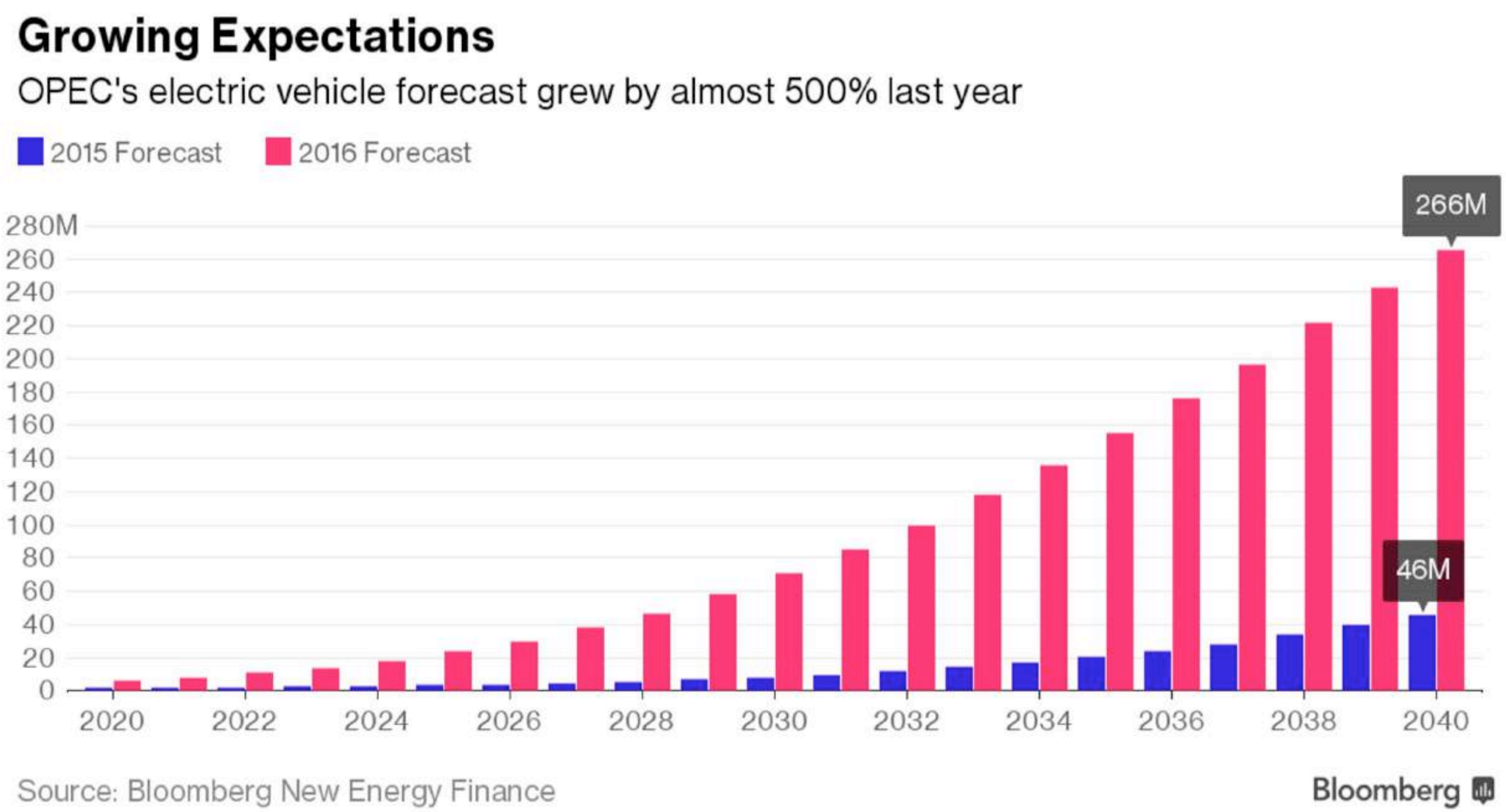
Refueling infrastructure:
Cost: 500-1000 k€ per station
FCH-JU is focusing most funding on infrastructure

Situazione al Marzo 2021

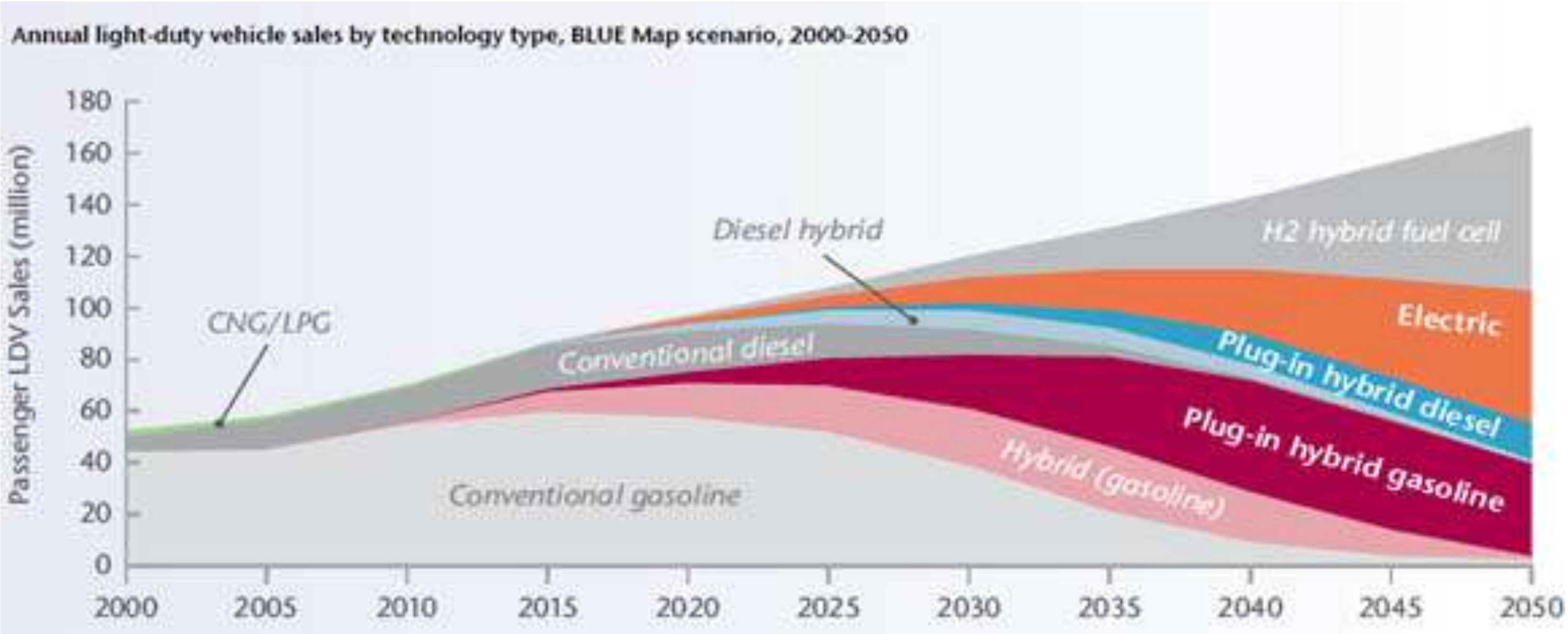
H2 Stations Map



Mobile storage forecast



light-duty electric vehicle forecasts



Seigo Kuzumaki - Toyota's head of advanced R&D and engineering: "internal combustion engine will power only about 10% of new vehicles as part of a hybrid system by 2050. All the remaining will be electrical"

Survey of Global Activity to Phase Out Internal Combustion Engine Vehicles

By Isabella Burch and Jock Gilchrist

Edited by Ann Hancock and Gemma Waaland

September 2018 Revision

Originally published February 2018

Country	Status of ICE Vehicle Phase-Out	Date of Action
Austria	Official target: No new ICE vehicles sold after 2020[2] [3]	April 2016
Britain	Official target: No new ICE vehicles sold after 2040[4] (will not include hybrids)	July 2017
China	Official target: End production and sales of ICE vehicles by 2040[5]	September 2017
Costa Rica	Initiate complete phase-out of ICE vehicles by 2021[6]	April 2018
Denmark	Official target: 5,000 EVs on the road by 2019, tax incentive in place[7]	Since 2008[8]
France	Official target: No new ICE vehicles sold after 2040[9]	July 2017
Germany	No registration of ICE vehicles by 2030 (passed by Legislature); cities can ban diesel cars;[10] Federal court ruling supports law[11]	October 2016
India	Official target: No new ICE vehicles sold after 2030 (will likely hit 30% by 2030)[12] [13]	April 2017
Ireland	Official target: No new ICE vehicles sold after 2030[14], incentive program in place for EV sales[15]	July 2017

Japan	Incentive program in place for EV sales[17]	Since 1996[18]
Netherlands	Official target: No new ICE vehicles sold after 2030, phase-out begins 2025[19]	October 2017
Norway	Incentive program in place for EV sales; Official target: only sell EVs by 2025[20]	Since 1990
Portugal	Official target and incentive in place for EV sales[21]	Since 2010[22]
Scotland	Official target: No new ICE vehicles sold after 2032[23]	September 2017
South Korea	Official target: EVs account for 30% of auto sales by 2020[24]	June 2016
Spain	Official government program: the *Movea 2017 Plan,* an incentive package to promote sales of alternative energy vehicles[25]	June 2017
Taiwan	Official target: Phase out fossil fuel-powered motorcycles by 2035 and fossil fuel-powered vehicles by 2040.[26] Additionally, the replacement of all government vehicles and public buses with electric versions by 2030.[27]	December 2017

4 novembre 2020

Ferrari Will Never Go Fully Electric, CEO Says

Ferrari CEO Louis Camilleri backed away from previous statements about the company's electrification plans

POLITICHE COMUNITARIE A SOSTEGNO DELLA MOBILITA' ELETTRICA

Joint Undertaking on Fuel Cells and Hydrogen 2 (FCH2) accelerates market introduction of clean and efficient technologies in energy and transport

Powering a climate-neutral economy: Commission sets out plans for the energy system of the future and clean hydrogen

The Commission proposed today (**23/02/21**) to set up 10 new European Partnerships between the European Union, Member States and/or the industry. The goal is to speed up the transition towards a green, climate neutral and digital Europe, and to make European industry more resilient and competitive. The EU will provide nearly **€10 billion** of funding that the partners will match with at least an equivalent amount of investment.

Clean Hydrogen: This partnership will accelerate the development and deployment of a European value chain for clean hydrogen technologies, contributing to sustainable, decarbonised and fully integrated energy systems. Together with the **Hydrogen Alliance**, it will contribute to the achievement of the Union's objectives put forward in the EU hydrogen strategy for a climate-neutral Europe. It will focus on producing, distributing and storing clean hydrogen and, on supplying sectors that are hard to decarbonise, such as heavy industries and heavy-duty transport applications.

Battery 2030+ / Batteries Europes

We are starting our research journey! BATTERY 2030+, a large-scale research initiative, initiates the first phase of inventing the sustainable batteries of the future. With a total budget of **EUR 40,5 million**, seven projects will contribute to the implementation of ultrahigh-performance, reliable, safe, sustainable and affordable batteries.

grazie dell'attenzione!

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