ENERGY STORAGE:
from hearing-aids to hydropower

Bill David

ISIS Facility, Rutherford Appleton Laboratory &
Inorganic Chemistry Laboratory, University of Oxford

UNIVERSITY OF OXFORD

ISIS

I·SEE
Institute for Sustainable Energy and the Environment

James Watt 1736-1819

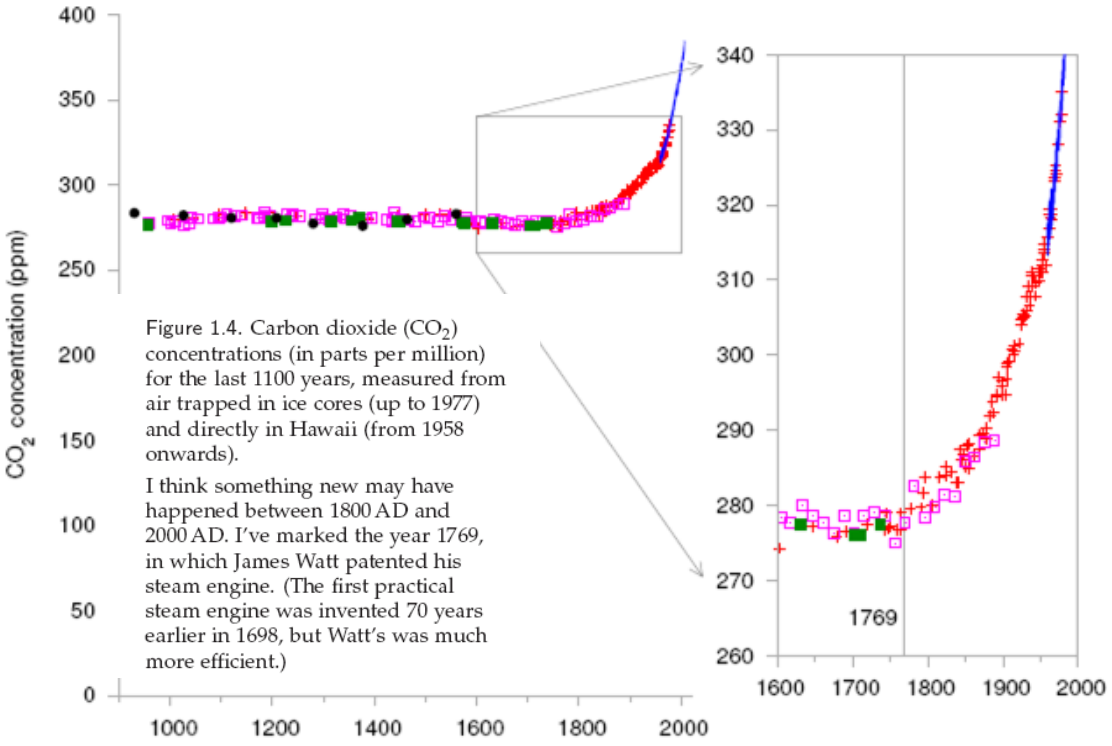
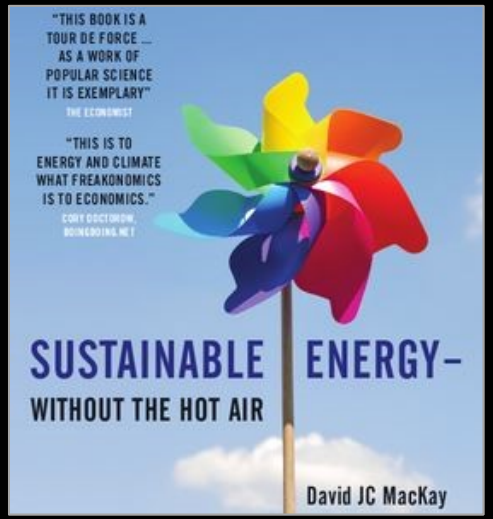


Figure 1.4. Carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards).

I think something new may have happened between 1800 AD and 2000 AD. I've marked the year 1769, in which James Watt patented his steam engine. (The first practical steam engine was invented 70 years earlier in 1698, but Watt's was much more efficient.)



www.withouthotair.com

1769

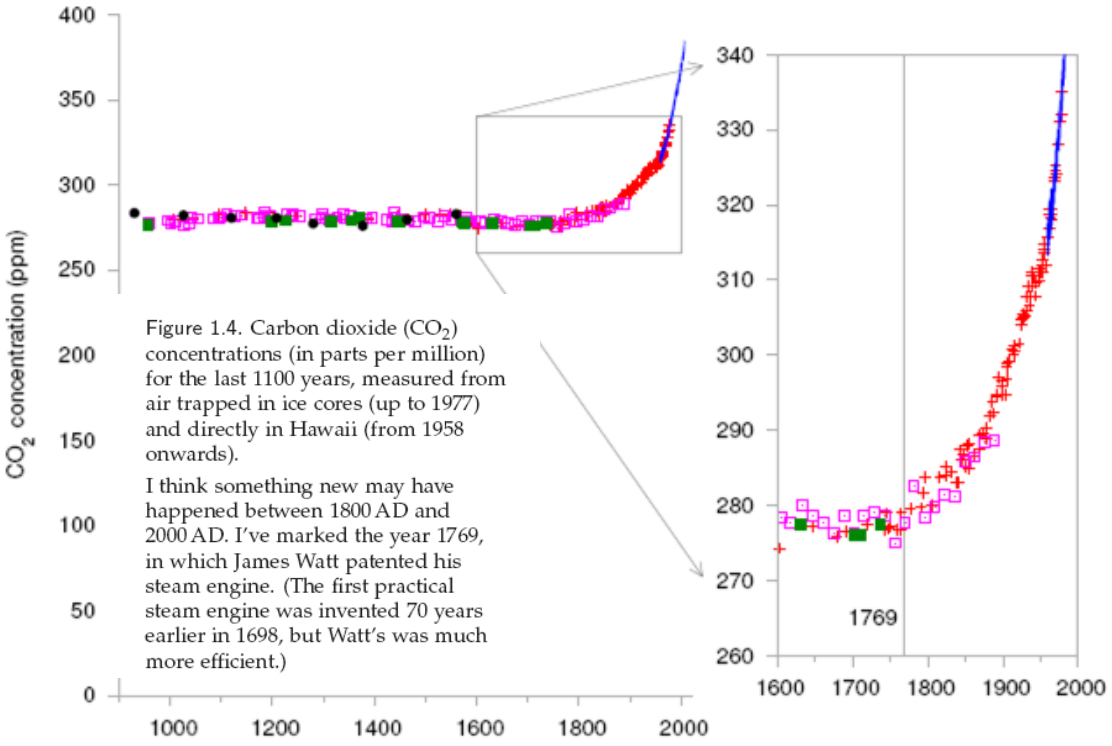
1969

"Once small step for a man, one giant leap for mankind"

Neil Armstrong, 20th July 1969, Tranquility Base, Moon

1969

2019



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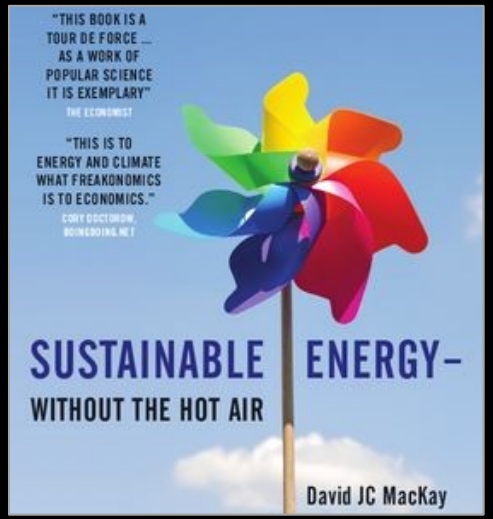
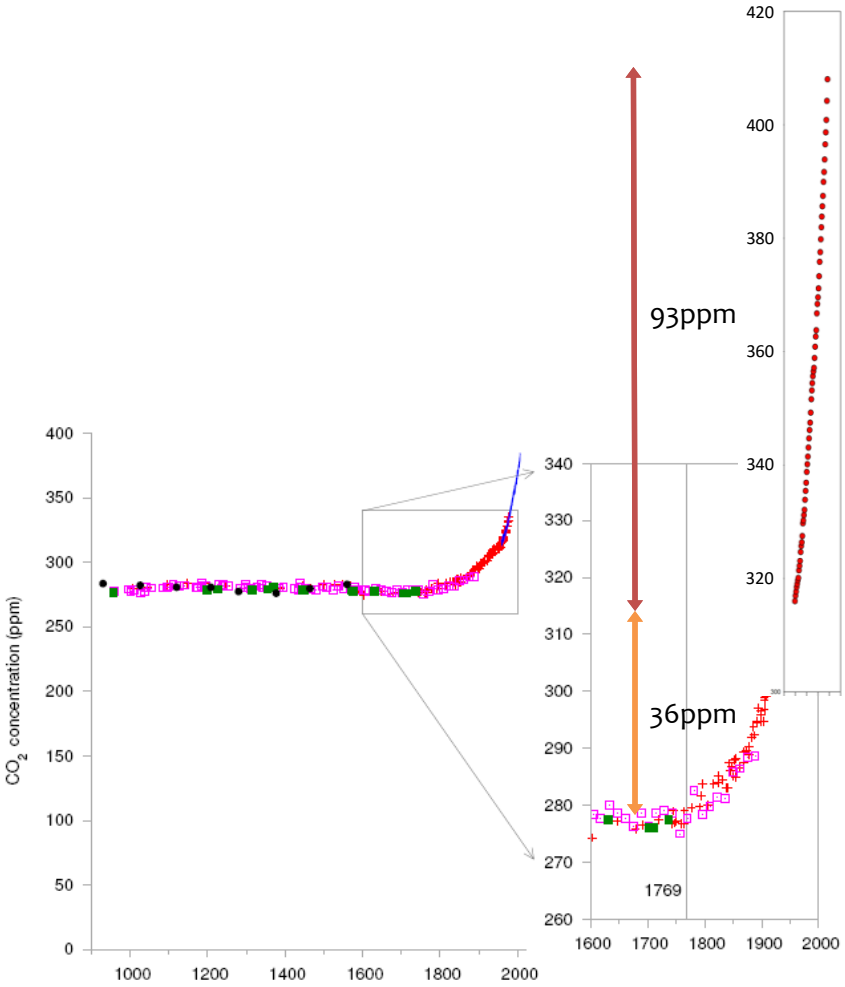
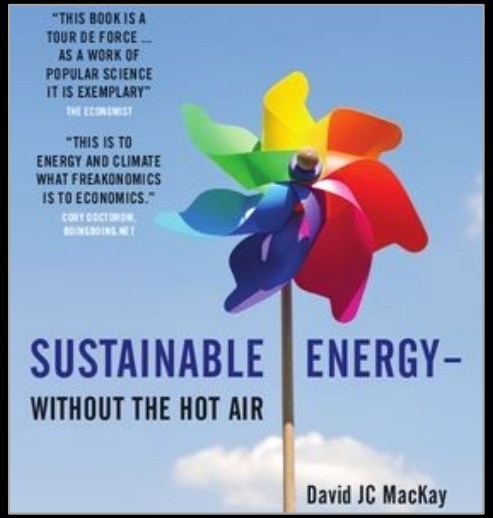


www.withouthotair.com





www.withouthotair.com

ENERGY PRODUCTION

Hydroelectric

Solar

Biomass

Marine

Wind

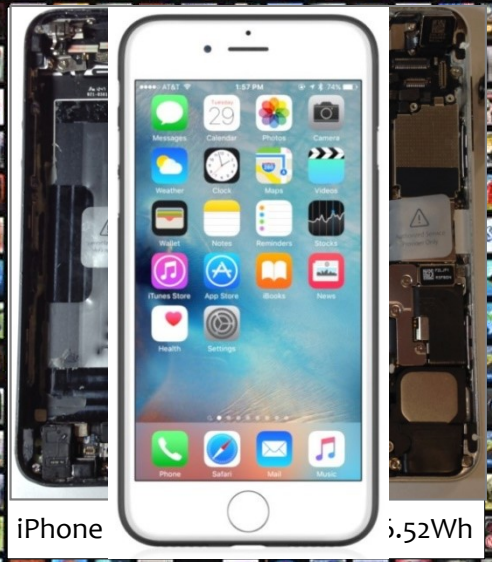
Gas/ Oil

Geothermal

Nuclear

Coal


ENERGY STORAGE



iPhone .52Wh

100MW

iPencil battery | 27mW | 329mWh

TESLA South Australia | 100MW (peak) | 129MWh

129MWh

× 4×10^9

× 4×10^8

27mW

iPhone | Li battery | 3.8W | 6.52Wh

TESLA S | 580kW (peak) | 100kWh

329mWh

POWER

ENERGY

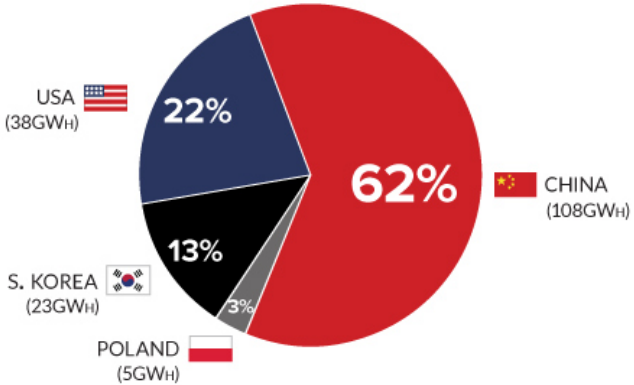
Press release

Business Secretary to establish UK as world leader in battery technology as part of modern Industrial Strategy

From: Innovate UK, Department for Business, Energy & Industrial Strategy, and The Rt Hon Greg Clark MP
Part of: Industrial Strategy Challenge Fund: joint research and innovation
Published: 24 July 2017

Business Secretary Greg Clark announces the launch of the £246 million Faraday Challenge to boost expertise in battery technology.

- Business Secretary announces first phase of its £246 million investment in battery technology as he launches Industrial Strategy's landmark 'Faraday Challenge'
- first phase includes launch of £45 million 'Battery Institute' competition to establish a centre for battery research to make technology more accessible and affordable
- Business Secretary to give keynote Industrial Strategy speech later today in Birmingham where he will also outline cutting-edge energy plans to break down barriers to new technologies and business models



By 2020, mass production of lithium-ion batteries will still be concentrated in just **four countries.**

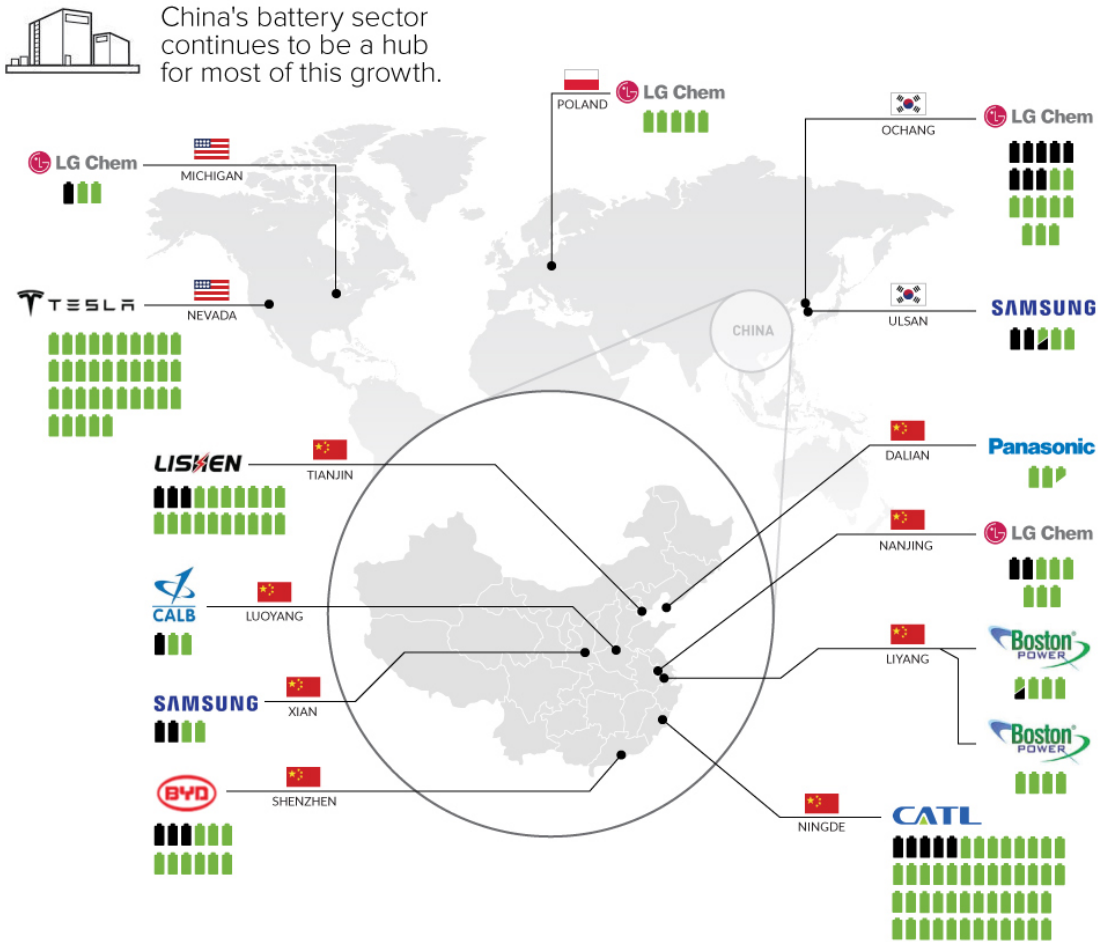
Data by:

BENCHMARK MINERAL INTELLIGENCE

visualcapitalist.com

China Leading the Charge for Lithium-Ion Megafactories

www.visualcapitalist.com/china-leading-charge-lithium-ion-megafactories/



www.visualcapitalist.com/china-leading-charge-lithium-ion-megafactories/

HOME MARKETS TECHNOLOGY ENERGY MINING GREEN MONEY POLITICS SPONSORED INFOGRAPHICS

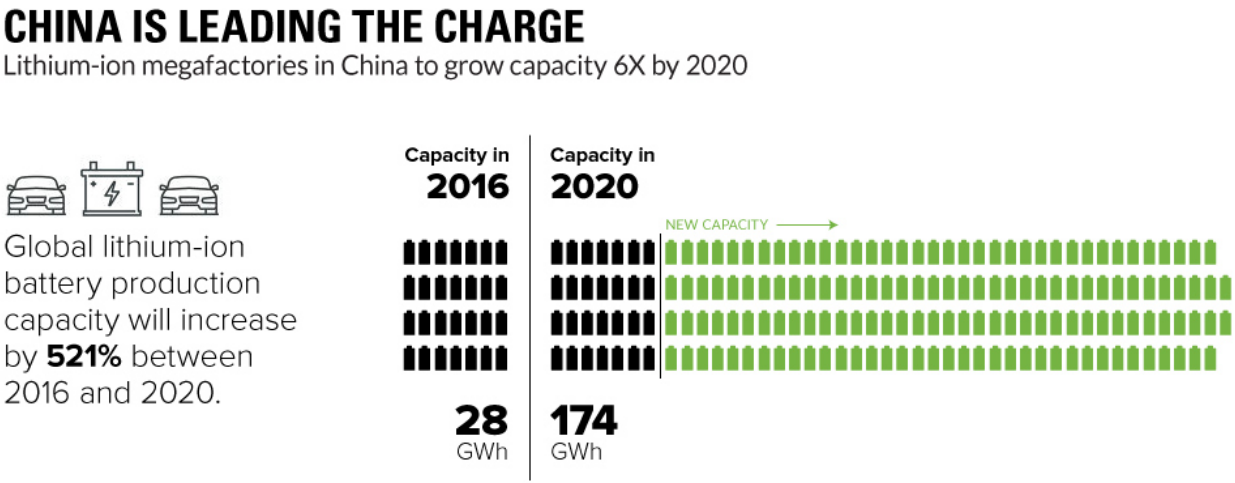
China Leading the Charge for Lithium-Ion Megafactories

VISUAL CAPITALIST

JEFF DESJARDINS on February 17, 2017 at 11:48 am

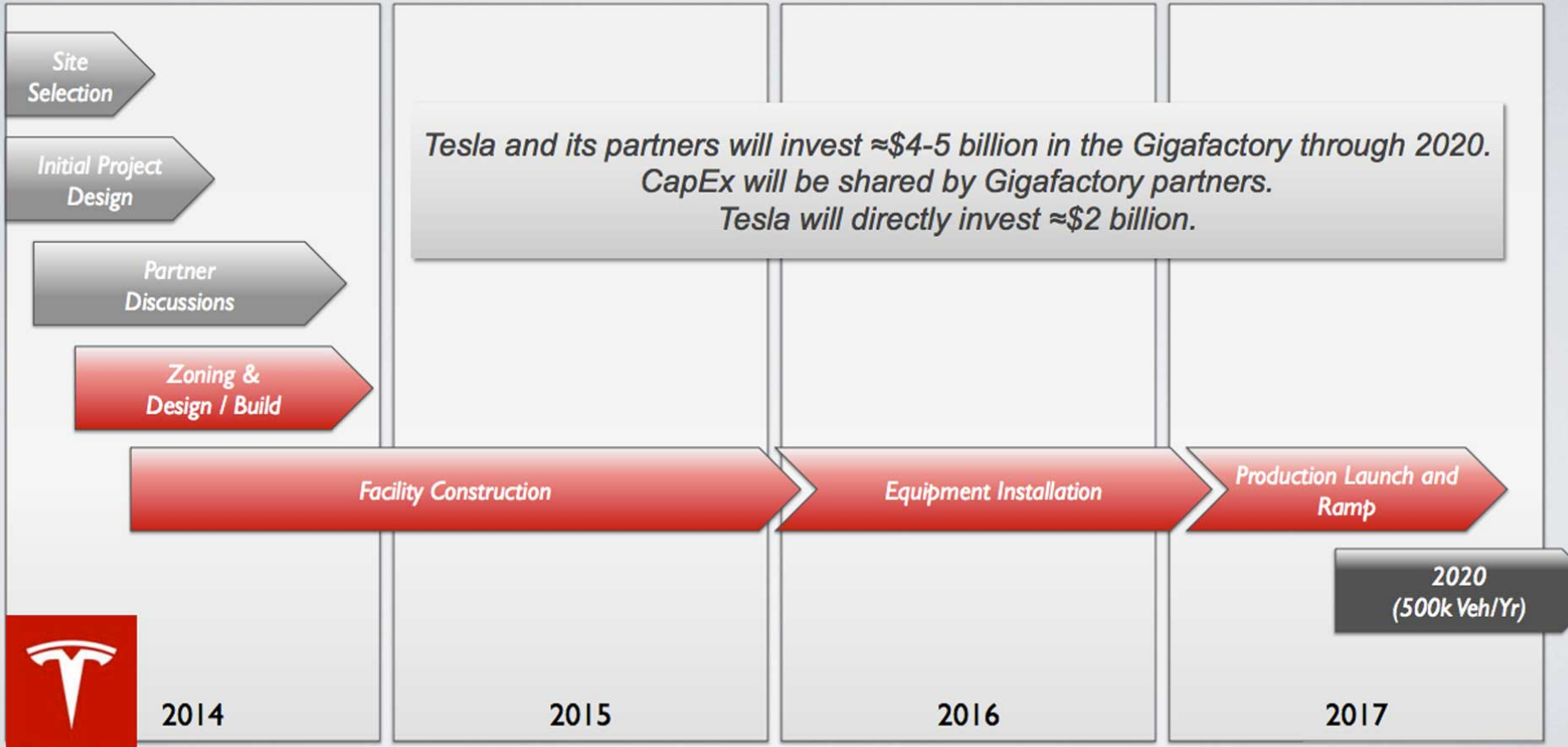
778 SHARES

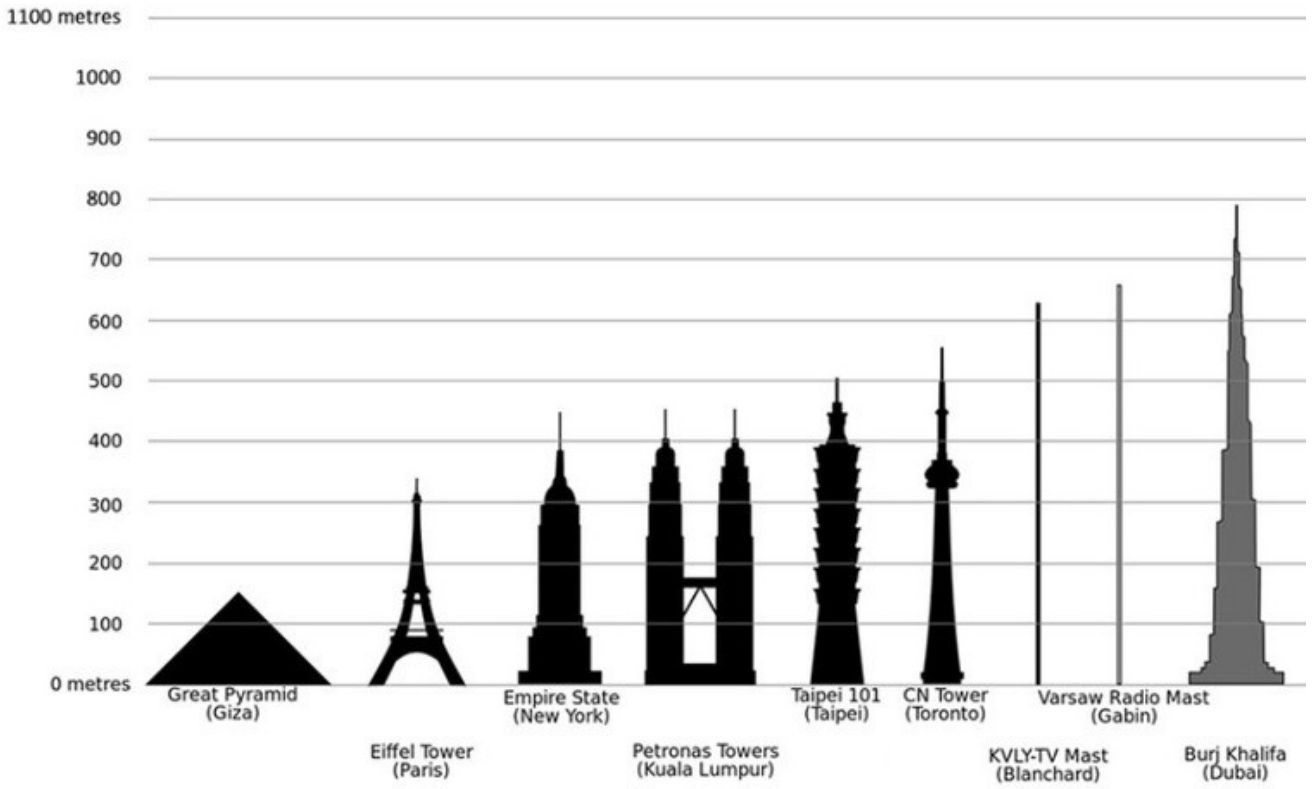
Chart of the Week



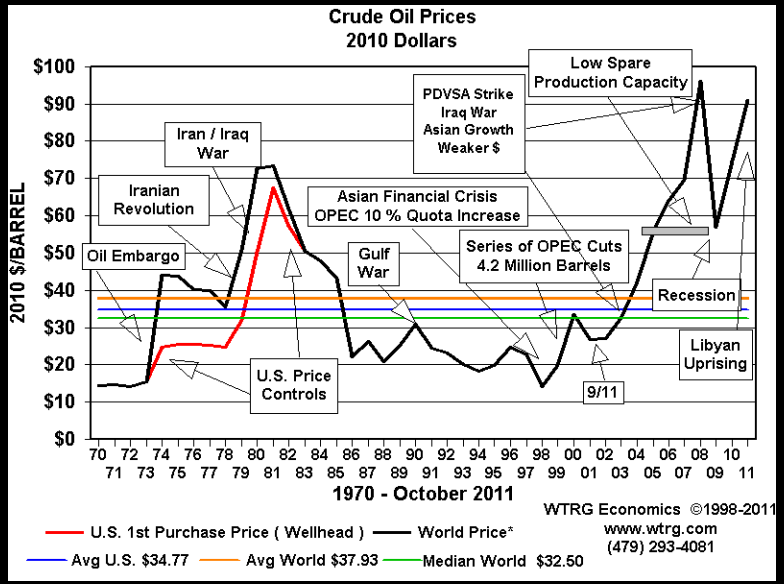
www.visualcapitalist.com/china-leading-charge-lithium-ion-megafactories/

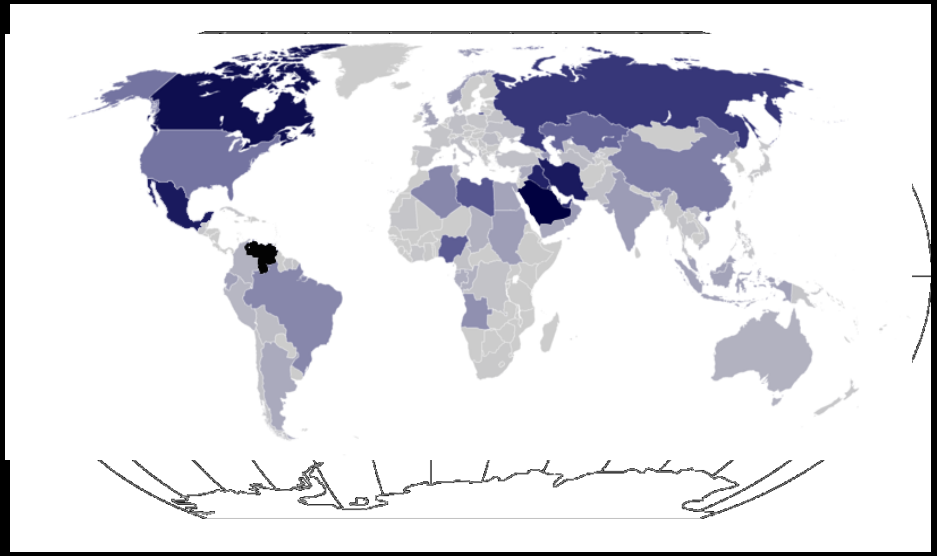
Gigafactory Projected Timeline

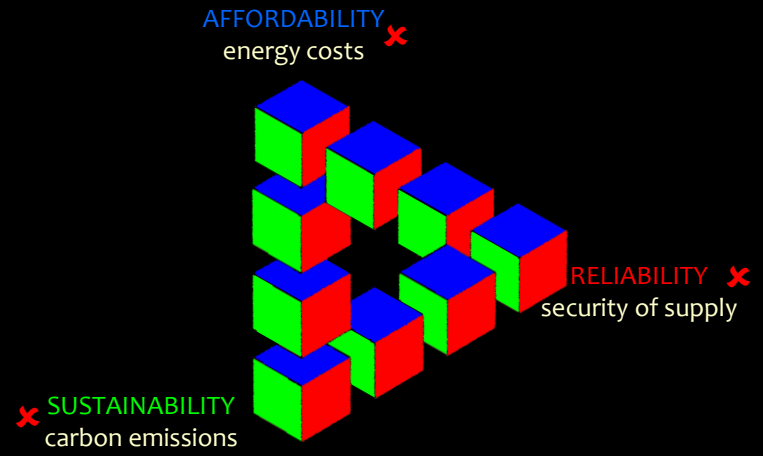



1100 metres
1000
900
800
700
600
500
400
300
200
100
0 metres
Great Pyramid (Giza)
Eiffel Tower (Paris)
Empire State (New York)
Petronas Towers (Kuala Lumpur)
Taipei 101 (Taipei)
CN Tower (Toronto)
KVLY-TV Mast (Blanchard)
Varsaw Radio Mast (Gabin)
Burj Khalifa (Dubai)

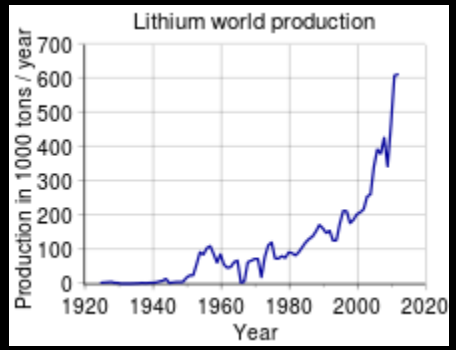
OIL RESERVES

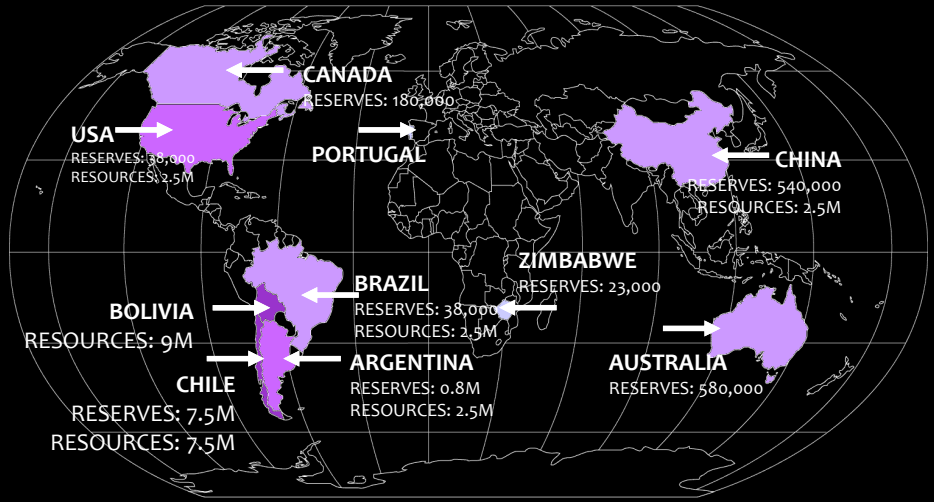






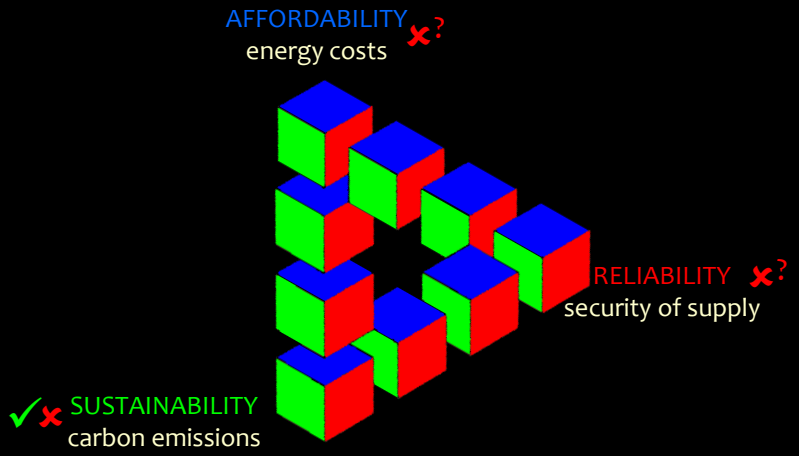
Li RESERVES

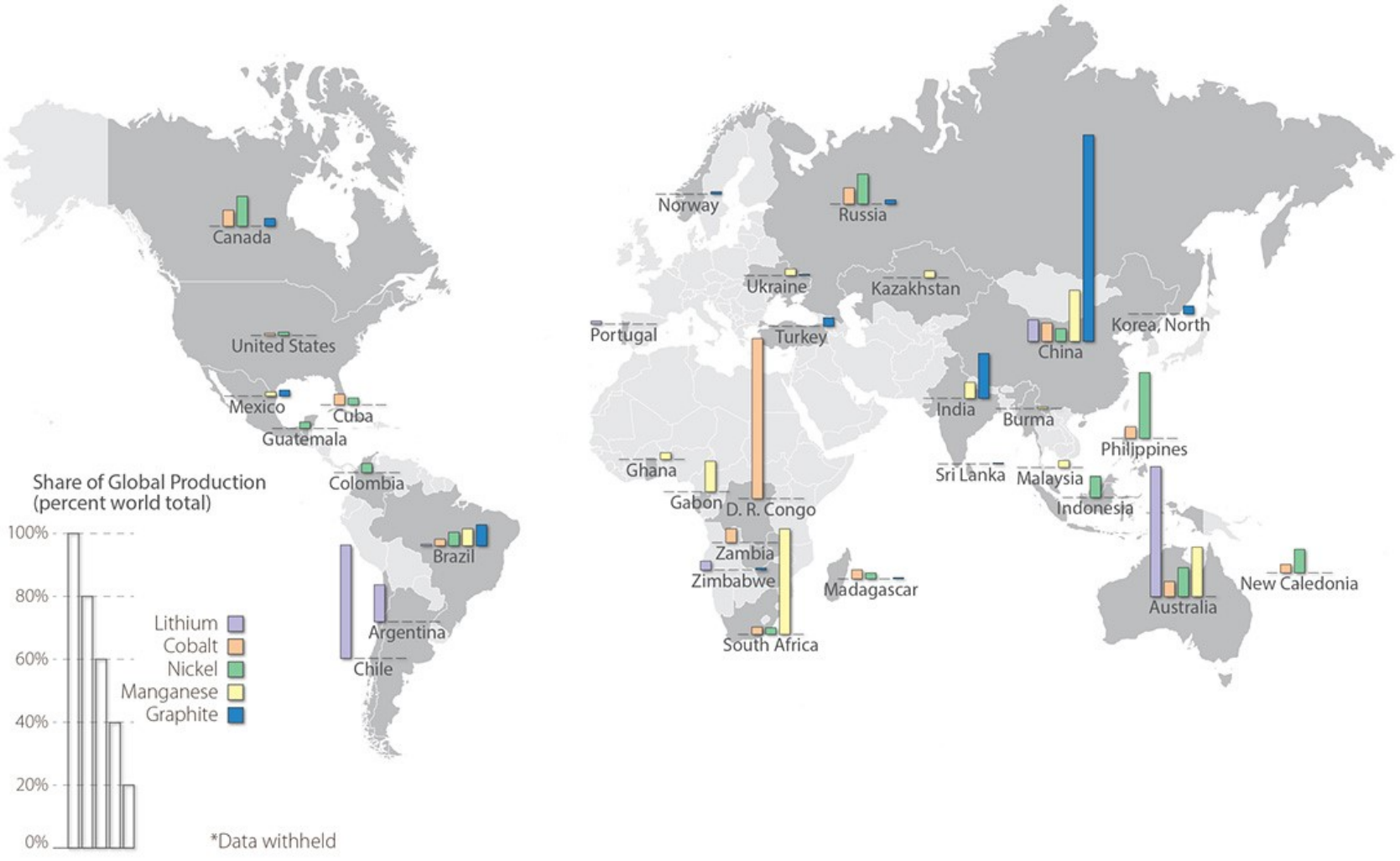




SALAR DE UYUNI | BOLIVIA

50% to 70% of the world's lithium reserves




Canada
United States
Mexico
Cuba
Guatemala
Colombia
Brazil
Argentina
Chile
Share of Global Production
(percent world total)
100%
80%
60%
40%
20%
0%
Lithium
Cobalt
Nickel
Manganese
Graphite
*Data withheld
Norway
Russia
Ukraine
Kazakhstan
Portugal
Turkey
China
Korea, North
India
Burma
Philippines
Sri Lanka
Malaysia
Indonesia
Ghana
Gabon
D. R. Congo
Zambia
Zimbabwe
Madagascar
South Africa
Australia
New Caledonia

Volvo

All Volvo cars to be electric or hybrid from 2019

Landmark move as first big manufacturer says it will stop making vehicles solely powered by internal combustion engine

Sales of Volvo's hybrid XC90 have been stronger than expected. Photograph: Volvo

This article is 5 months old

17,707 852

Adam Vaughan

@adamvaughan_uk

Wednesday 5 July 2017 12.26 BST

Automotive industry

France to ban sales of petrol and diesel cars by 2040

Move by Emmanuel Macron's government comes a day after Volvo said it would only make fully electric or hybrid cars from 2019

Angelique Chrisafis and Adam Vaughan

Thursday 6 July 2017 14.20 BST

Renault's Zoe electric car will escape France's ban after 2040. Photograph: Renault

He said it would be a "tough" objective for carmakers but France's industry was well equipped to make the switch. "Our [car]makers have enough ideas in the drawer to nurture and bring about this promise ... which is also a public health issue."

Hulot insisted that the decision was a question of public health policy and "a way to fight against air pollution". The veteran environmental campaigner was among several political newcomers to whom Macron gave top jobs in his government.

Pascal Canfin, the head of WWF France and a former Green politician who served in François Hollande's government, said the new policy platform to counter climate change went further than previous administrations in France. "It places France among the leaders of climate action in the world," he told France Inter radio.

Air pollution

Britain to ban sale of all diesel and petrol cars and vans from 2040

Plans follow French commitment to take polluting vehicles off the road owing to effect of poor air quality on people's health

Anushka Asthana and Matthew Taylor

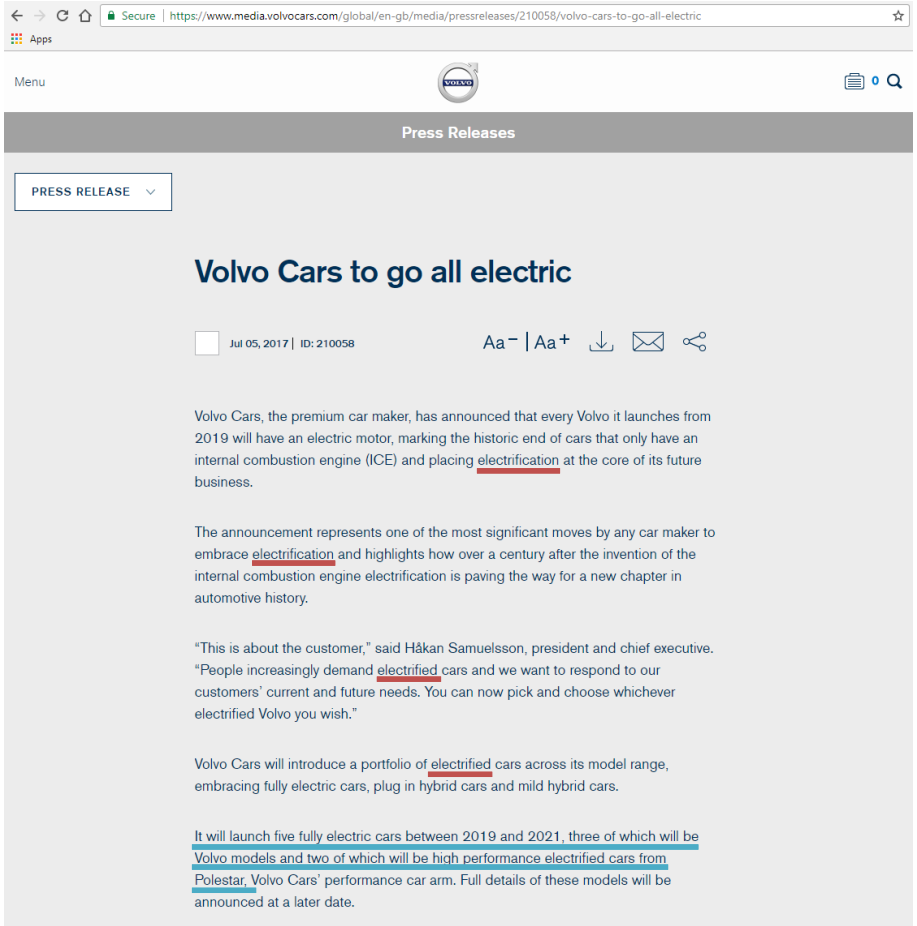
Tuesday 25 July 2017 22.38 BST

Ministers believe poor air quality poses largest environmental risk to public health in UK. Photograph: Peter

Britain is to ban all new petrol and diesel cars and vans from 2040 amid fears that rising levels of nitrogen oxide pose a major risk to public health.

The commitment, which follows a similar pledge in France, is part of the government's much-anticipated clean air plan, which has been at the heart of a protracted high court legal battle.

The government warned that the move, which will also take in hybrid vehicles, was needed because of the unnecessary and avoidable impact that poor air quality was having on people's health. Ministers believe it poses the largest environmental risk to public health in the UK, costing up to £2.7bn in lost productivity in one recent year.



Secure | https://www.media.volvocars.com/global/en-gb/media/pressreleases/210058/volvo-cars-to-go-all-electric

Apps

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Press Releases

PRESS RELEASE

Volvo Cars to go all electric

Jul 05, 2017 | ID: 210058

Aa− | Aa+

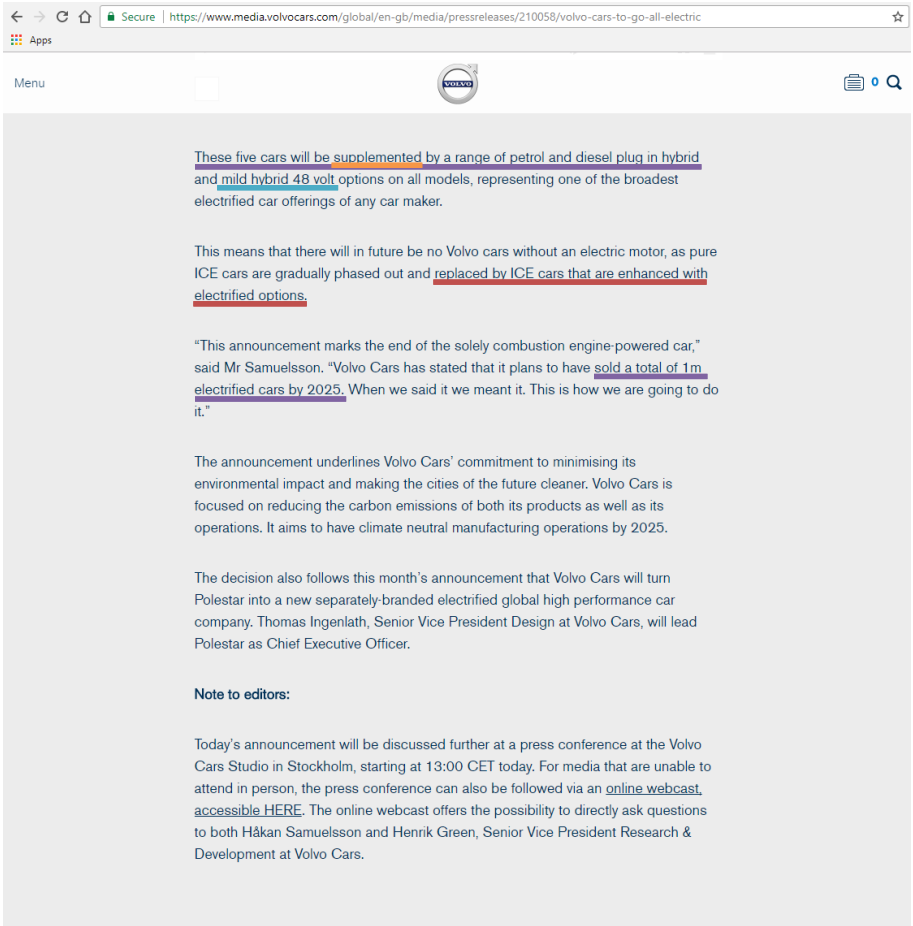
Volvo Cars, the premium car maker, has announced that every Volvo it launches from 2019 will have an electric motor, marking the historic end of cars that only have an internal combustion engine (ICE) and placing electrification at the core of its future business.

The announcement represents one of the most significant moves by any car maker to embrace electrification and highlights how over a century after the invention of the internal combustion engine electrification is paving the way for a new chapter in automotive history.

"This is about the customer," said Håkan Samuelsson, president and chief executive. "People increasingly demand electrified cars and we want to respond to our customers' current and future needs. You can now pick and choose whichever electrified Volvo you wish."

Volvo Cars will introduce a portfolio of electrified cars across its model range, embracing fully electric cars, plug in hybrid cars and mild hybrid cars.

It will launch five fully electric cars between 2019 and 2021, three of which will be Volvo models and two of which will be high performance electrified cars from Polestar, Volvo Cars' performance car arm. Full details of these models will be announced at a later date.



Secure | https://www.media.volvocars.com/global/en-gb/media/pressreleases/210058/volvo-cars-to-go-all-electric

Apps

Menu

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These five cars will be supplemented by a range of petrol and diesel plug in hybrid and mild hybrid 48 volt options on all models, representing one of the broadest electrified car offerings of any car maker.

This means that there will in future be no Volvo cars without an electric motor, as pure ICE cars are gradually phased out and replaced by ICE cars that are enhanced with electrified options.

"This announcement marks the end of the solely combustion engine-powered car," said Mr Samuelsson. "Volvo Cars has stated that it plans to have sold a total of 1m electrified cars by 2025. When we said it we meant it. This is how we are going to do it."

The announcement underlines Volvo Cars' commitment to minimising its environmental impact and making the cities of the future cleaner. Volvo Cars is focused on reducing the carbon emissions of both its products as well as its operations. It aims to have climate neutral manufacturing operations by 2025.

The decision also follows this month's announcement that Volvo Cars will turn Polestar into a new separately-branded electrified global high performance car company. Thomas Ingenlath, Senior Vice President Design at Volvo Cars, will lead Polestar as Chief Executive Officer.

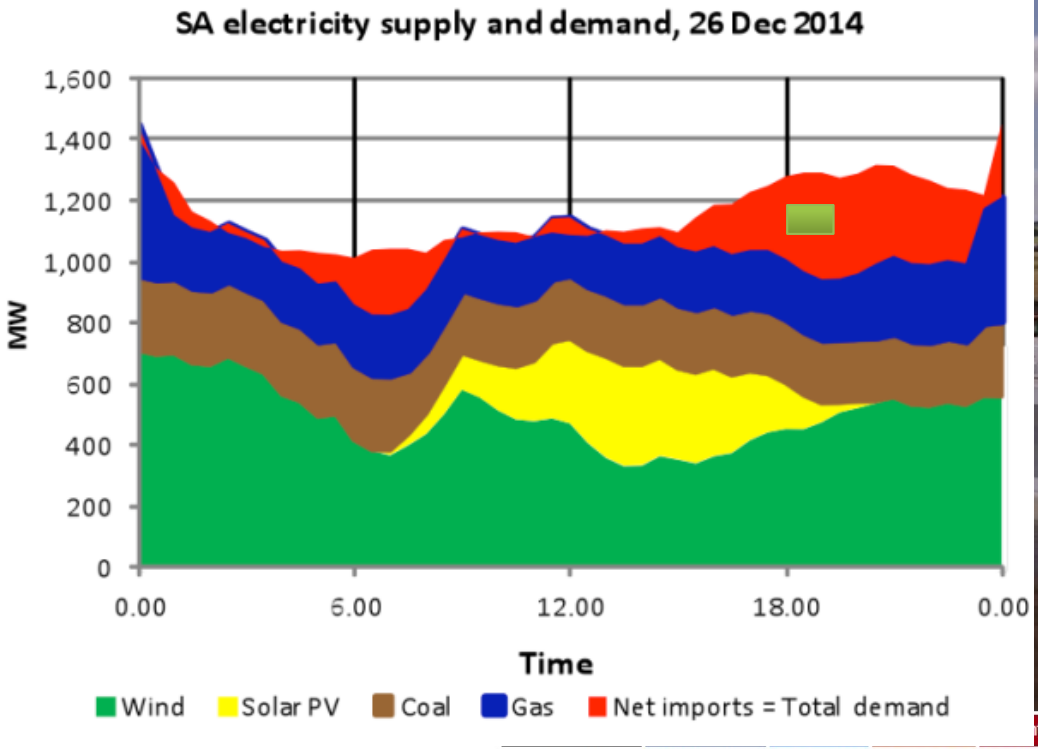
Note to editors:

Today's announcement will be discussed further at a press conference at the Volvo Cars Studio in Stockholm, starting at 13:00 CET today. For media that are unable to attend in person, the press conference can also be followed via an online webcast, accessible HERE. The online webcast offers the possibility to directly ask questions to both Håkan Samuelsson and Henrik Green, Senior Vice President Research & Development at Volvo Cars.

www.forbes.com/sites/michaeltaylor/2017/07/05/most-of-what-youve-read-on-volvos-electric-car-strategy-is-badly-misleading/

Tesla completes world's largest li-ion battery system in Australia

Fred Lambert - Nov. 23rd 2017 5:43 am ET @FredericLambert



ENERGY STORAGE

Hydroelectric

Solar

Biomass

Marine

Wind

Gas/ Oil

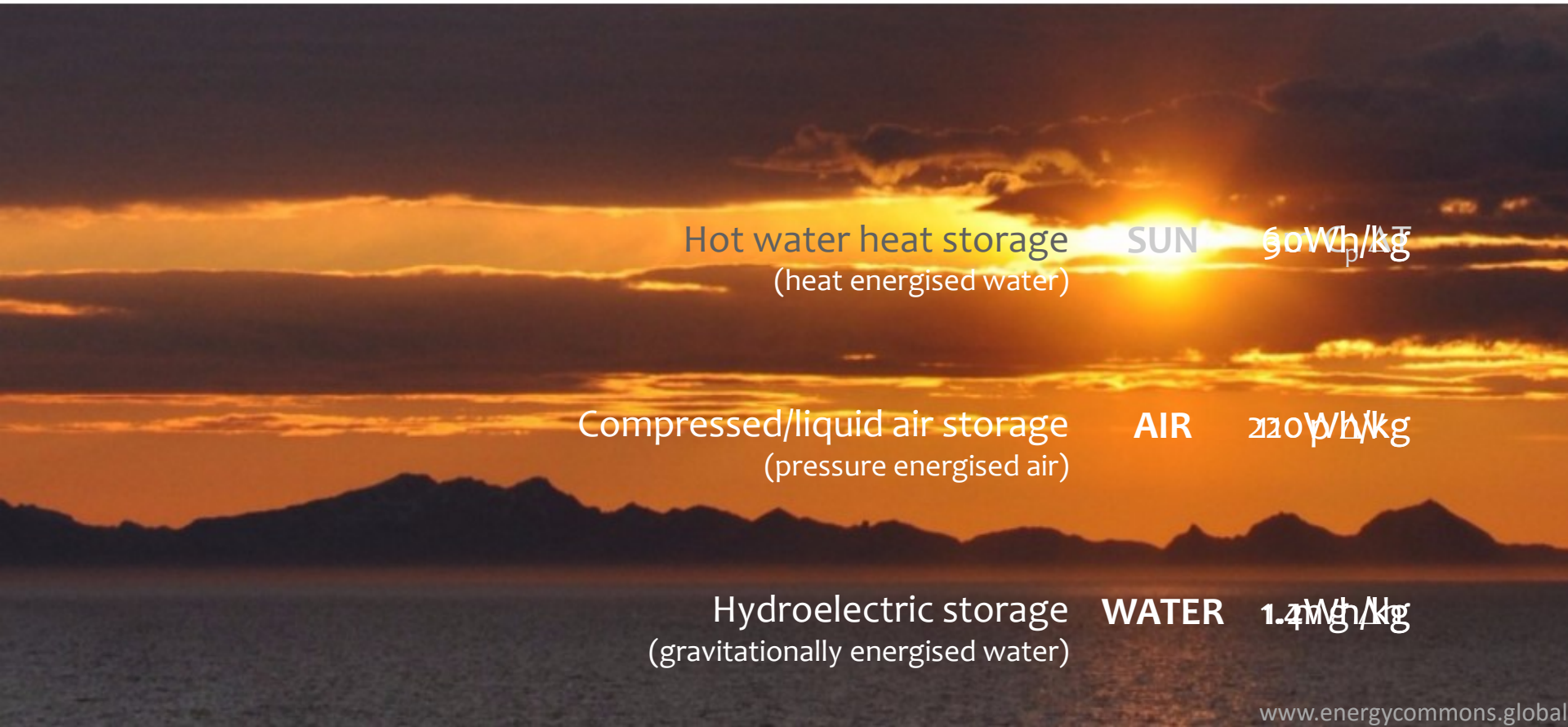
Geothermal

Nuclear

Coal

Can we use the Global Commons to store energy?


1.8GW (peak) | 9.1GWh
Pumped hydroelectric storage
Dinorwig, N Wales


Hot water heat storage
(heat energised water)
SUN
90 Wh/kg
Compressed/liquid air storage
(pressure energised air)
AIR
210 Wh/kg
Hydroelectric storage
(gravitationally energised water)
WATER
1.4 MWh/kg

Electricity storage

ΔH = -220Wh/kg (Li^+ battery)

… potential challenges with earth abundance of materials

SUN

(NH_3 = chemically energised water)

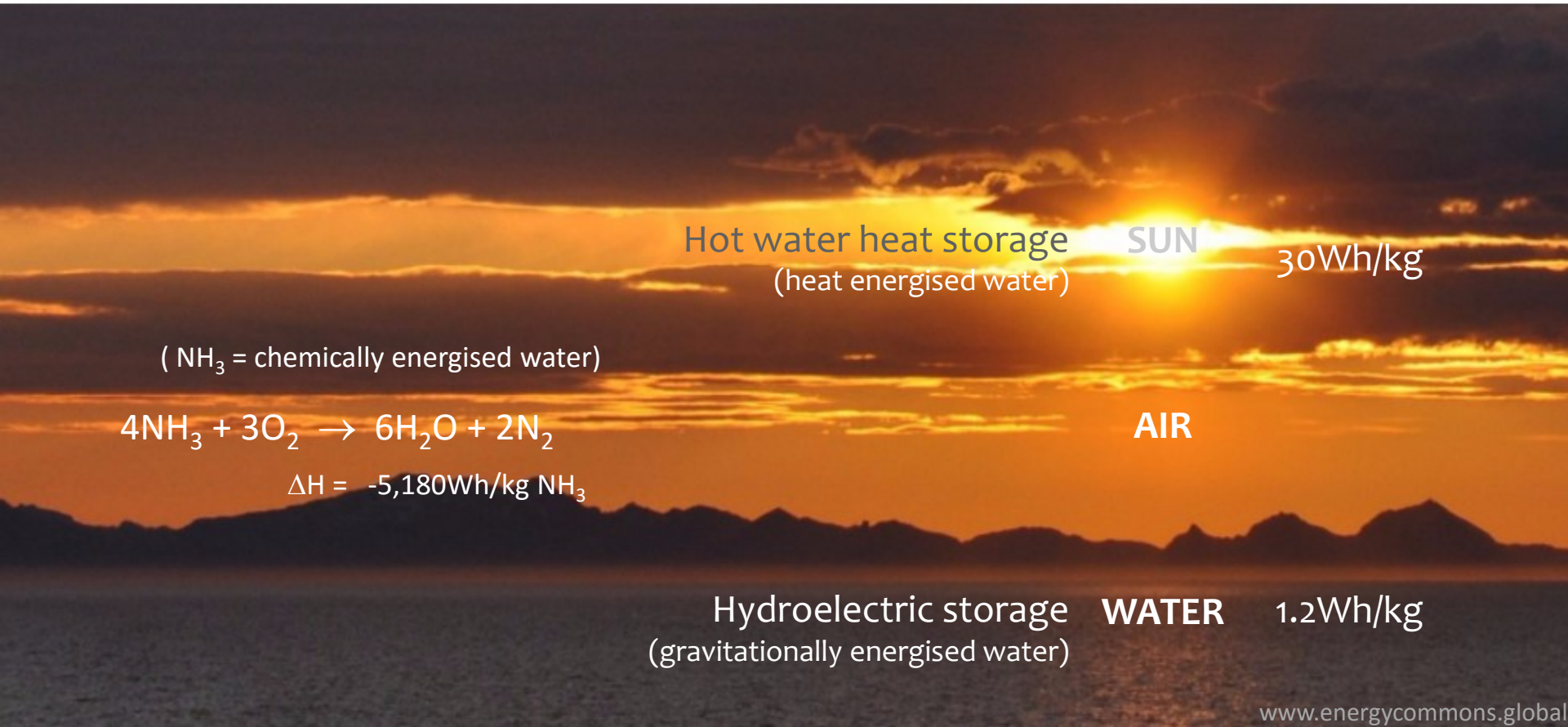
$4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2$ $\quad$ $N_2 + 3H_2 \rightarrow 2NH_3$ $\quad$ **AIR**

ΔH = -5,180Wh/kg NH_3

$4CH_4 + 8O_2 \rightarrow 8H_2O + 4CO_2$ $\quad$ $2H_2O \rightarrow 2H_2 + O_2$ $\quad$ **WATER**

ΔH = -12,777Wh/kg CH_4

… but storing & distributing hydrogen is challenging


Hot water heat storage
(heat energised water)
SUN
30Wh/kg
(NH_3 = chemically energised water)
$4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2$
ΔH = -5,180Wh/kg NH_3
AIR
Hydroelectric storage
(gravitationally energised water)
WATER
1.2Wh/kg

TESLA GIGAFACTORY, SPARKS, NEVADA

Tesla's mission is to accelerate the world's transition to sustainable energy through increasingly affordable electric vehicles and energy products. To achieve its planned production rate of 500,000 cars per year by 2018, Tesla alone will require today's entire worldwide supply of lithium-ion batteries. The Tesla Gigafactory was born out of necessity and will supply enough batteries to support Tesla's projected vehicle demand.

Tesla broke ground on the Gigafactory in June 2014 outside Sparks, Nevada. The name Gigafactory comes from the word "Giga," the unit of measurement representing "billions." The factory's planned annual battery production capacity is 35 gigawatt-hours (GWh), with one GWh being the equivalent of generating (or consuming) 1 billion watts for one hour. This is nearly as much as the entire world's current battery production combined.

Gigafactory construction, on November 4, 2014

35GWh/year

October 7, 2016

November 9 , 2016

December 18 , 2016

March 14, 2017

April 10, 2017

May 9, 2017

June 16, 2017

$5B

July 15, 2017

510,000m^2

TEESSIDE TERAFACTORY

600,000t NH_3/year ≅ 0.38 × 0.6 × 4.4 TWh/year

1 Mtoe = 4.4TWh ≅ 1.00 TWh/year

≅ 30 Gigafactories

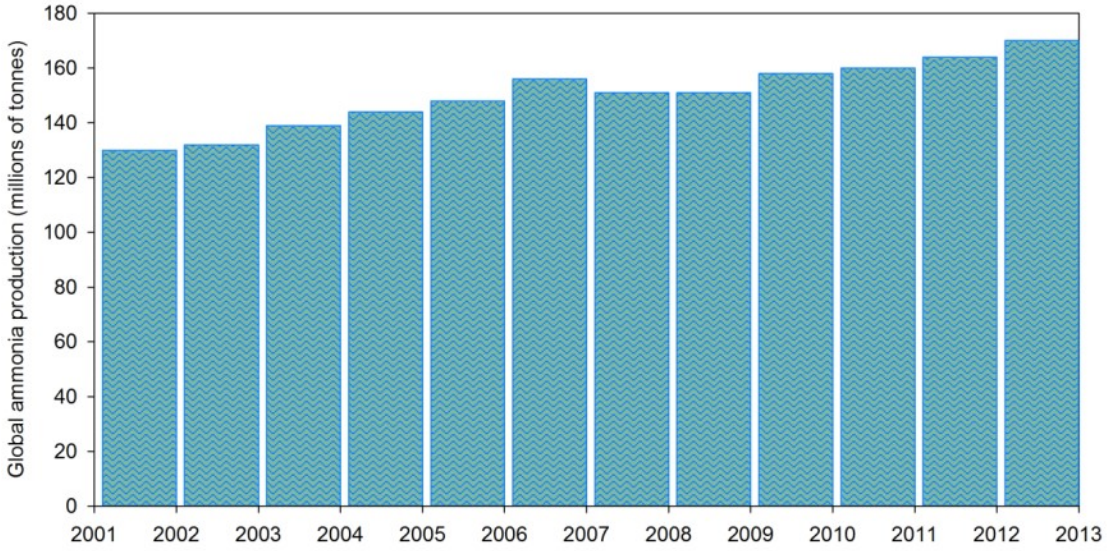
≅ 170 Gigafactories (cost) | 450 Gigafactories (area)


Fritz Haber


Carl Bosch

Artificial NH_3 synthesis
The Haber-Bosch process

1909 | 1910



source: www.potashcorp.com/industry_overview/2011/nutrients/41/

nature International weekly journal of science

Millennium Essay

Nature **400**, 415 (29 July 1999) | doi:10.1038/22672

Detonator of the population explosion

Without ammonia, there would be no inorganic fertilizers, and nearly half the world would go hungry. Of all the century's technological marvels, the Haber-Bosch process has made the most difference to our survival.

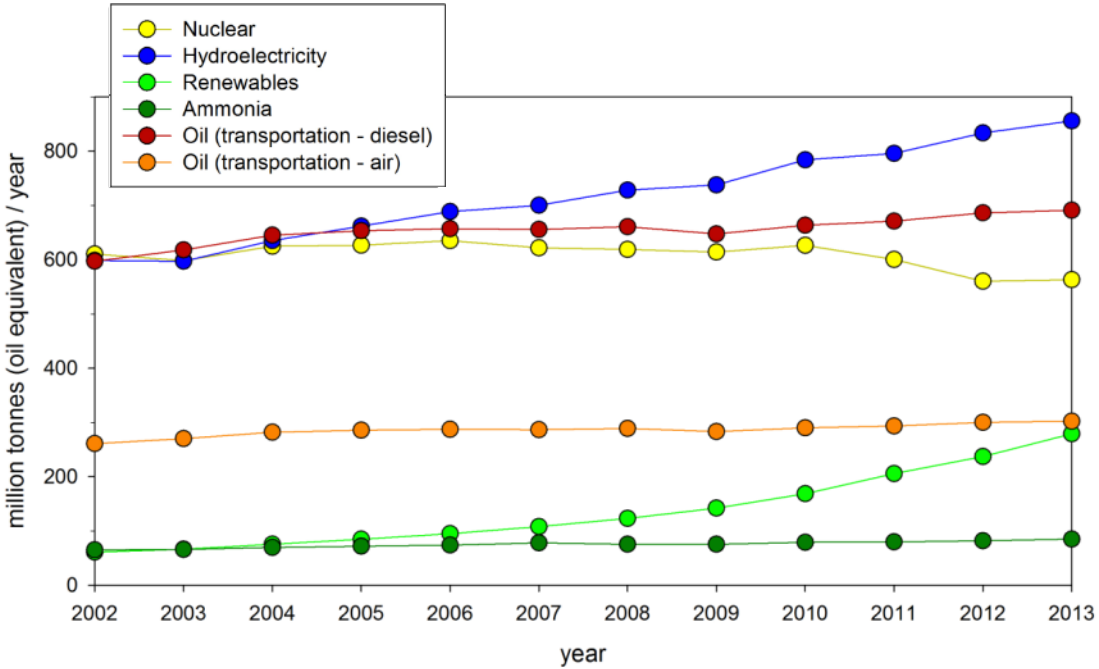
- 170 million tonnes / year
- 1% world's energy use
- 2% global CO_2 emissions
- 40% nitrogen in our bodies

PHYSICAL PROPERTIES

- 17.6wt% hydrogen
- liquid @ 8bar (298K)
- storage same as butane/propane
- heat of combustion: 6.3kWh/kg
  c.f. (petrol) 13.1kWh/kg

Artificial NH_3 synthesis
The Haber-Bosch process

1909 | 1910



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nature International weekly journal of science
Millennium Essay
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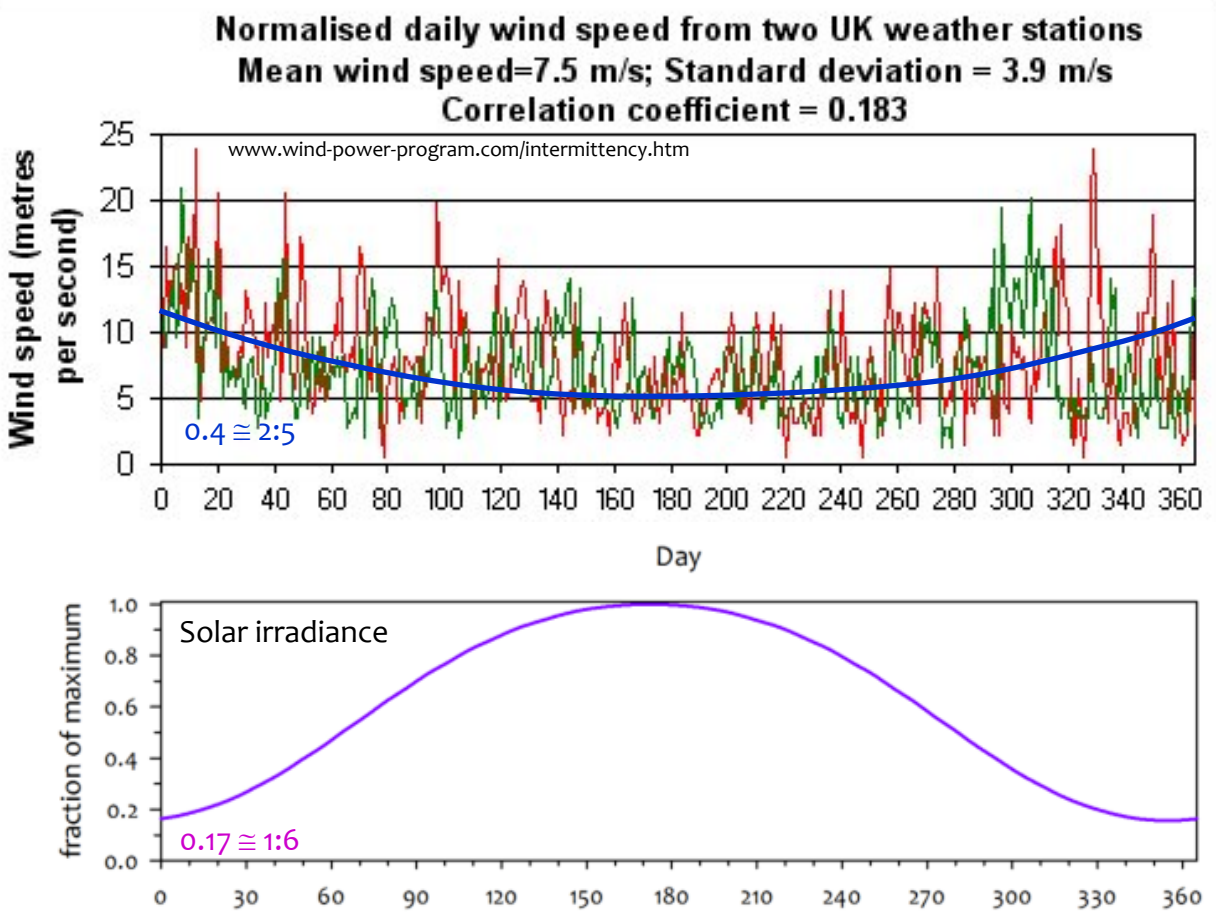
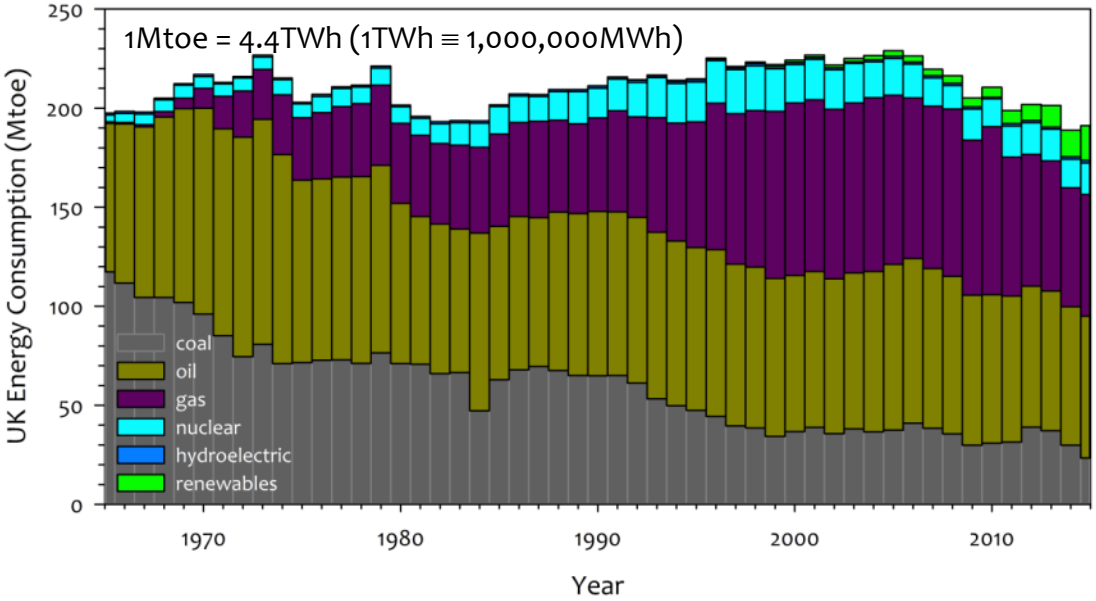

Normalised daily wind speed from two UK weather stations
Mean wind speed=7.5 m/s; Standard deviation = 3.9 m/s
Correlation coefficient = 0.183
www.wind-power-program.com/intermittency.htm
Wind speed (metres per second)
0.4 ≅ 2:5
Day
Solar irradiance
fraction of maximum
0.17 ≅ 1:6



South Australia (TESLA)

130MWh ≡ 650 × Powerpack 2
100MW peak power
Footprint ≅ 1.0 hectare
Cost ≅ US$50M

UK 10 days (TESLA)

$200 \times 4.4 \times 10^6 \times (10/365)$ MWh
24 million MWh ≡ 120 million × Powerpack 2
Footprint ≅ 1850km²
(London (M25) ~ 2800km²)
Cost ≅ US$9T

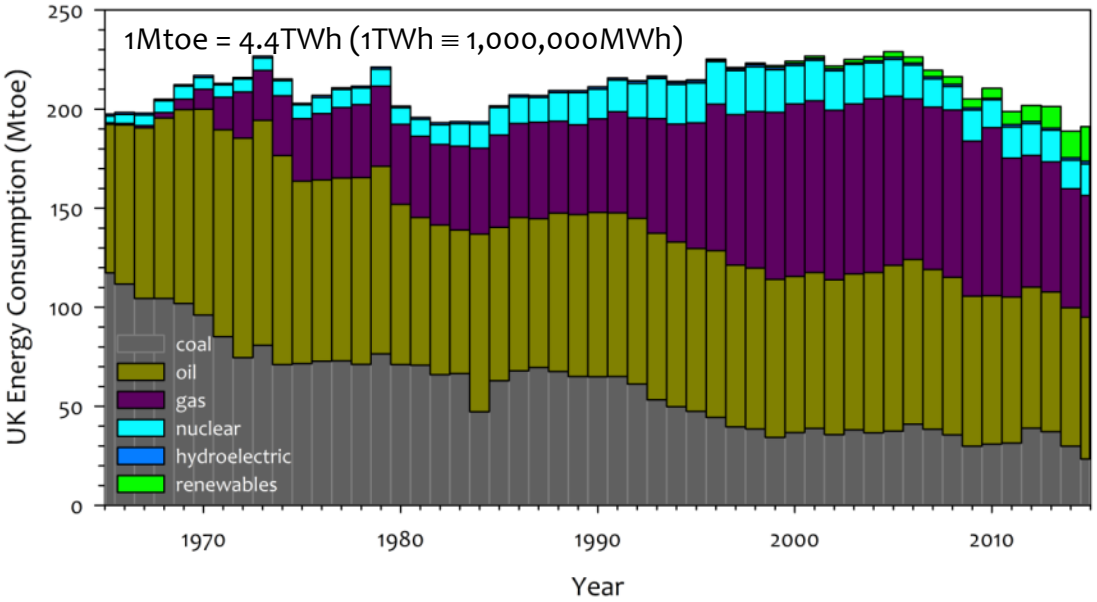
10 day oil storage: $200 \times (10/365)$Mt

$= 5.4 \times 10^6$ tonnes

$= 7.2 \times 10^6$ m³

= 60 oil storage tanks

≈ 60 ha = 0.6km²



South Australia (TESLA)

130MWh ≡ 650 × Powerpack 2
100MW peak power
Footprint ≅ 1.0 hectare
Cost ≅ US$50M

UK 10 days (TESLA)

$200 \times 4.4 \times 10^6 \times (10/365)$ MWh
24 million MWh ≡ 120 million × Powerpack 2
Footprint ≅ 1850km²
(London (M25) ~ 2800km²)
Cost ≅ US$9T

10 day NH_3 storage: $200 \times (10/365)$Mtoe

= 5.4 Mtoe

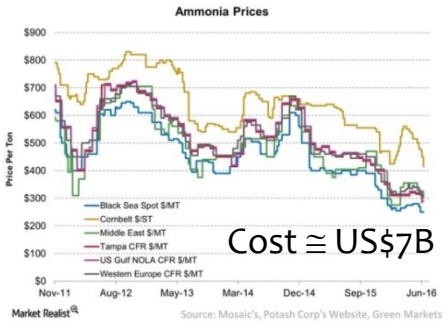
= $5.4 \times (44.8/22.5) \times 10^6$ tonnes

= 11×10^6 tonnes

= 18×10^6 m³

= 150 storage tanks

≈ 150 ha = 1.5km²



Cost ≅ US$7B

DEMOCRATISING ENERGY


Democratic Republic of the Congo


South Africa


Kenya


Paraguay


Columbia


East Timor


Bangladesh

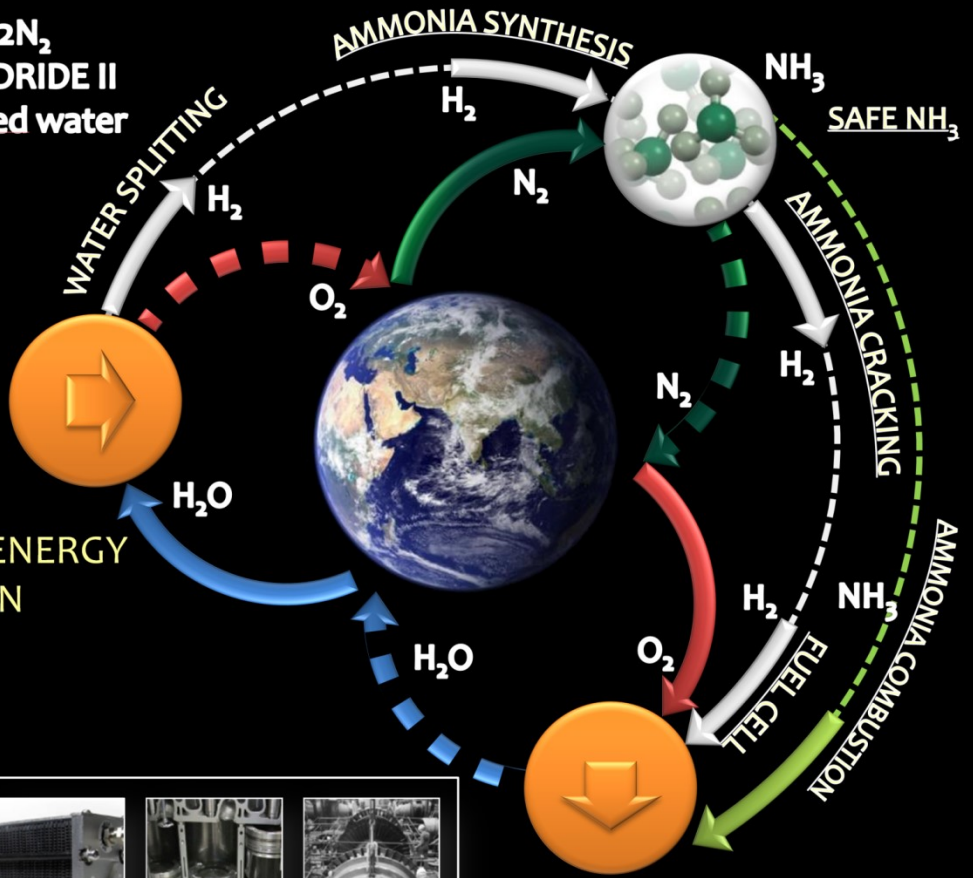

Cambodia

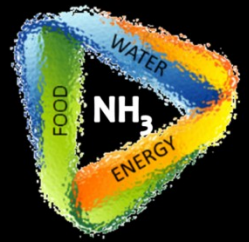

India

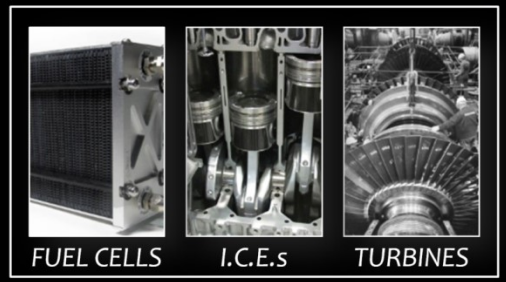
$4NH_3 + 3O_2 \leftrightarrow 6H_2O + 2N_2$

AIR HYDRIDE I ↔ AIR HYDRIDE II

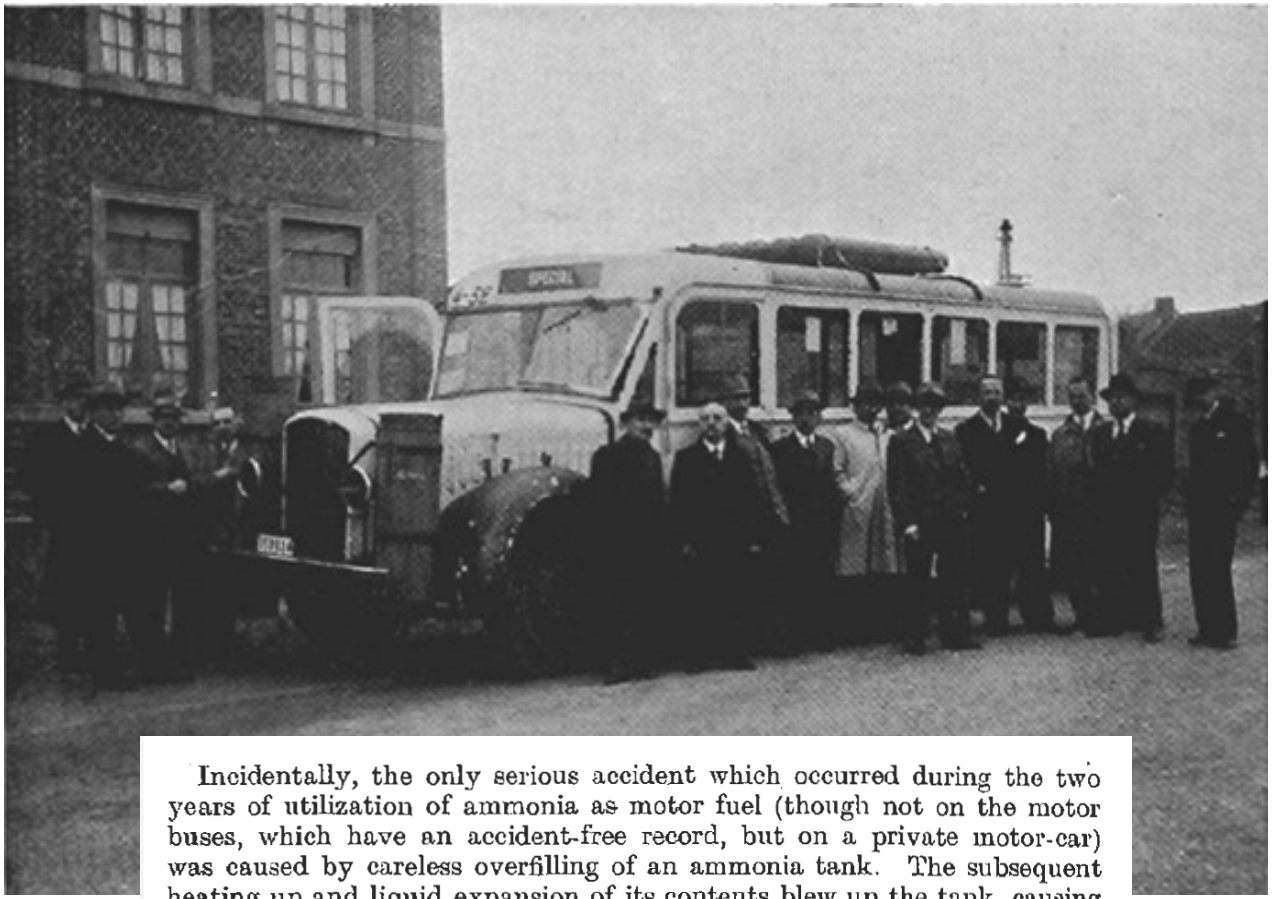
water ↔ energised water







THE WATER : AMMONIA CYCLE



Incidentally, the only serious accident which occurred during the two years of utilization of ammonia as motor fuel (though not on the motor buses, which have an accident-free record, but on a private motor-car) was caused by careless overfilling of an ammonia tank. The subsequent heating up and liquid expansion of its contents blew up the tank, causing some material damage, but no casualties.

Electricity storage

ΔH = -220Wh/kg (Li^+ battery)

… potential challenges with earth abundance of materials

Hot water heat storage — SUN — 30Wh/kg
(heat energised water)

(NH_3 = chemically energised water)

$4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2$ — **AIR** — 110Wh/kg

ΔH = -5,180Wh/kg NH_3

Hydroelectric storage — **WATER** — 1.2Wh/kg
(gravitationally energised water)