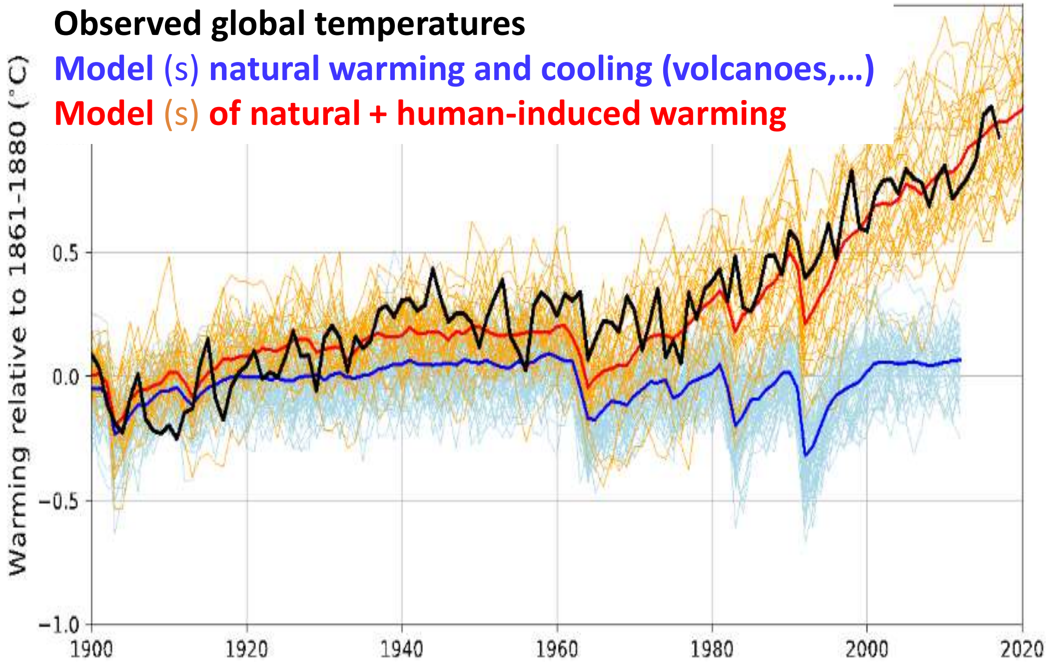
The Energy Transition
and
the Role of Physicists

Chris Llewellyn Smith

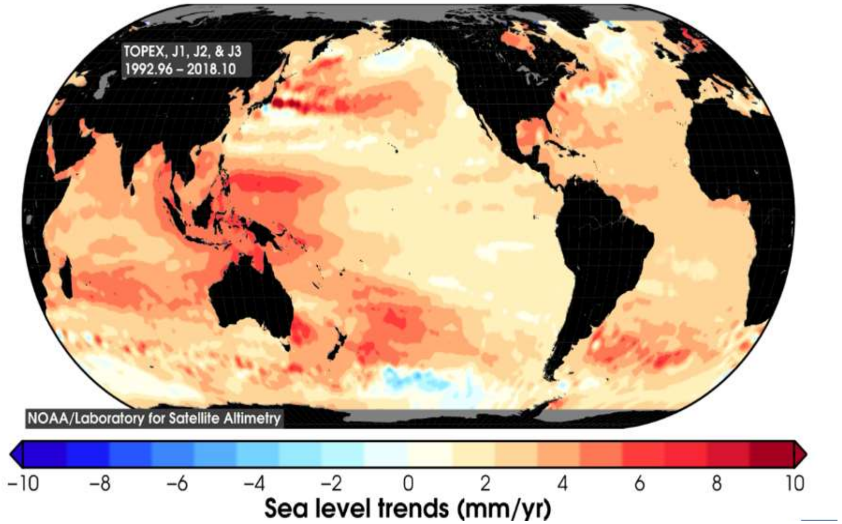
Oxford University

Why transition to low/zero carbon is needed:

Climate Change – temperature increasing, as predicted



Example of impact:

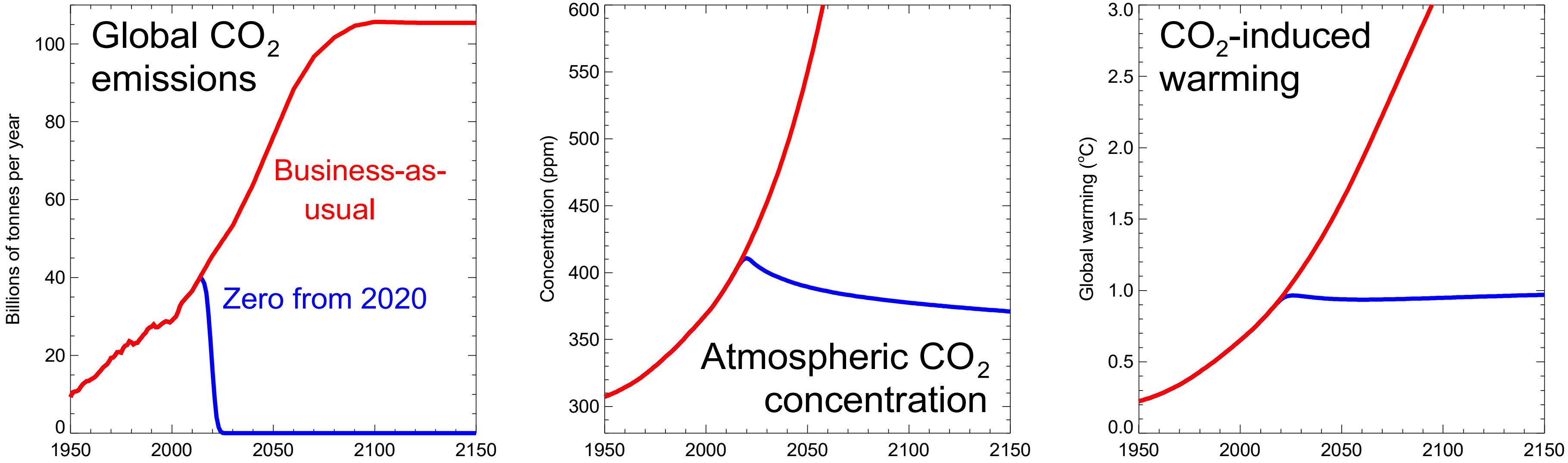


Sea level rise in line with predictions

Air pollution → 7 million deaths pa (WHO 2018: outdoor/indoor pollution → 4.2 m/3.8 m)
13% of total of 55 million deaths pa – on average, 10 year loss of life
Biggest effects in India, China… but about 6% of deaths in UK

Improve security of supply in countries without large fossil fuel reserves and
rebalance their relations with countries with reserves

CO2 emissions have a permanent, cumulative effect on temperature



Implication: emissions must stop altogether, or we must remove CO2 from atmosphere - not enough to slow down

Good tutorial on climate change @ http://www.eci.ox.ac.uk/news/2018/0410.html

The destination is enshrined in the Paris Agreement accepted by all but one country

- Hold the increase in the global average temperature to well below 2 °C above pre-industrial levels* and *(as increasingly stressed)* pursue efforts to limit the temperature increase to 1.5 °C

  …reach global peaking of greenhouse gas emissions as soon as possible … achieve a balance between emissions by sources and removals by sinks … in the second half of this century …

* **Means:** parties to formulate increasingly ambitious Nationally Determined Contributions every five years *i.e. it's voluntary! Pledges currently nothing like enough to keep below + 2 C*

Does US withdrawal matter? Yes – but it's not critical

States control much of energy policy and **the primary challenge is to develop alternatives that are as cheap, or cheaper, than fossil fuels - which is happening**

Although it weakens Paris pledge that developed countries will help to finance decarbonisation in developing countries

Since Paris: agreements on international

Aviation – all emissions (rising 3% pa) above 2020 level to be off-set

Shipping – emissions at least 50% less by 2050 → "Most new ships built in 2030 will have to have zero emissions"

We should be decarbonising, but there's a long way to go:

Thermal equivalent primary energy

2017: Fossil – 77.8%, Bio + Waste - 9.0%, Hydro - 6.3%, Nuclear - 4.1%, Wind - 1.7%, Solar - 0.7%, Geo - 0.1%

Moving target. By 2040 World energy use expected to grow by some 35% (fossils + 18%)

The rise is in the poorer (non-OECD) counties:

OECD → - 4% (population + 9%)

Non-OECD* (currently 61% of total) → + 47% (70% of total), population + 27%, per capita energy + 16%

where 1.1 bn [2.8 bn] lack electricity [clean cooking facilities] and more energy is needed to enable decent lives

Per capita energy use in 2016 (IEA) - toe						
USA	UK	China	Africa	India	Bangladesh	World
6.8	2.8	2.2	0.656	0.65	0.24	1.9

Climate Change – some good trends, but **very far from being on track to meet climate targets**

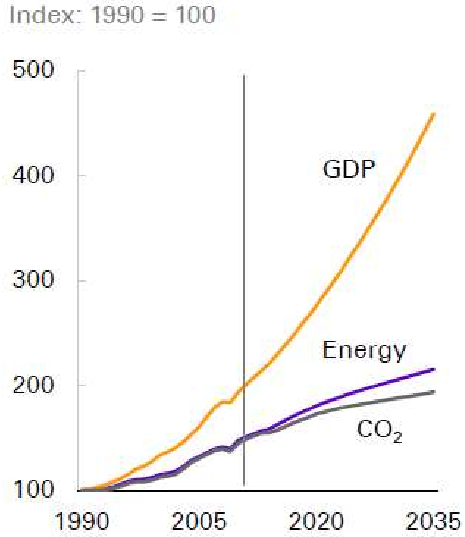
Air pollution - numbers very uncertain, but over its lifetime a large coal power station may kill some 100 times more people than Chernobyl. **Coming on to the public agenda** (VW has drawn attention to the problem)

Ways to Decarbonise

- Reduce demand – better planning
- Use energy more efficiently

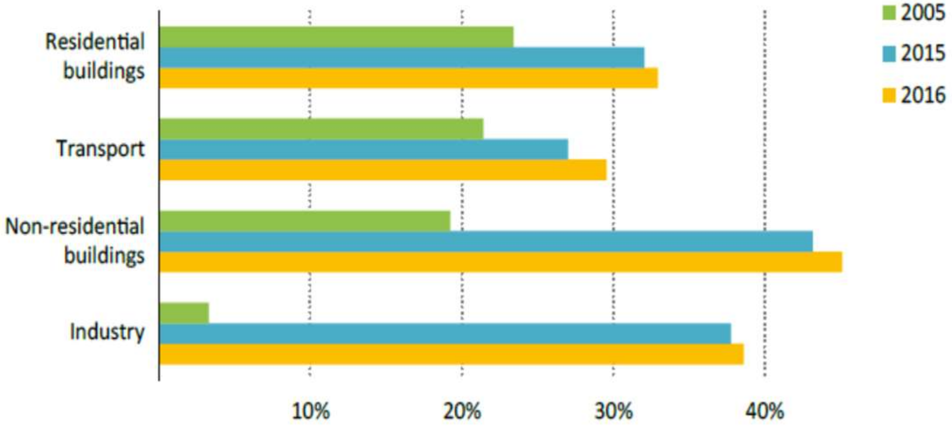
Essential but won't solve the problem

CO2/GDP is decreasing – but not fast enough:



Technically can do much better
Key is stronger regulation – happening:

Percentage of sector subject to regulation globally (IEA)



- Move to low carbon systems and sources + negative emissions

What to Decarbonise

- **Primary energy ends up providing** (global numbers)

  Heat ≈ Electricity *(some → heat and transport)* **≈ 37.5%, Transport ≈ 25%**

  Final energy: 50% heat, 30% transport, 20% electricity *(some → heat and transport)*

- **Electricity –** know how to decarbonise in principle
- **Heat* –** very hard to decarbonise
- **Transport* –** will probably mostly become electric (increase challenge of decarbonising electricity)

**more 'people sensitive' than electricity*

Need to look at whole **system** holistically – heat, transport, electricity, markets, economics, polices, *consumer acceptance of technologies & policies*

Decarbonising Heat

Globally heat → 49% buildings, 46% industry

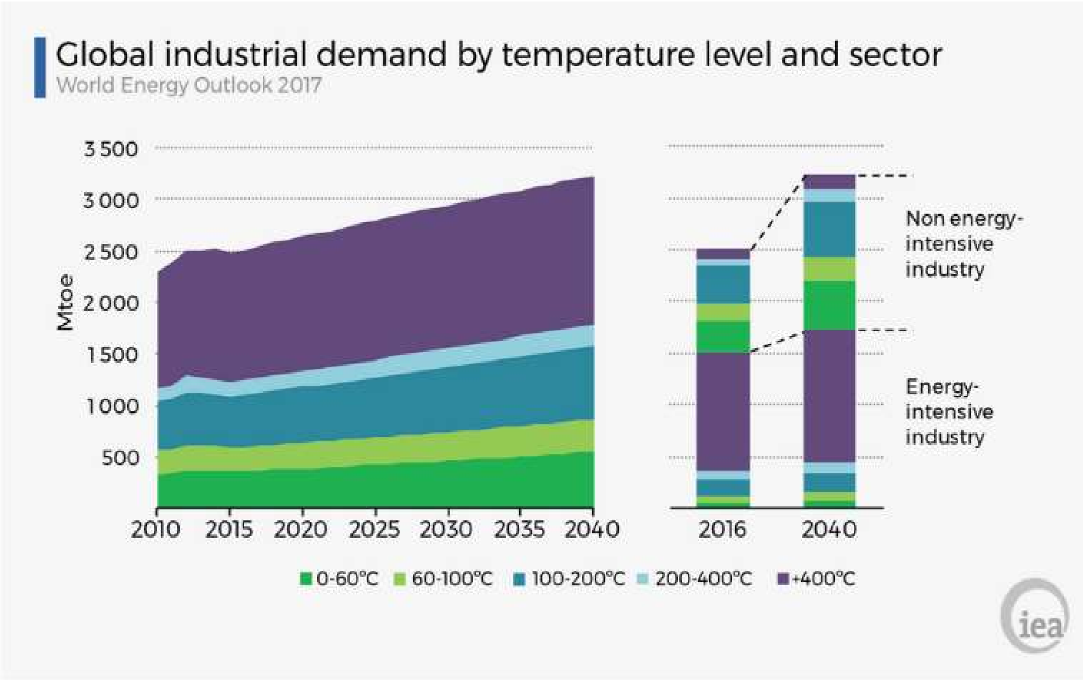
Buildings (cooling also an issue)

- **Better insulation**
- **Combined heat and power – spare heat from power plants* → district heating:** *64% of all homes in Denmark – 98% in Copenhagen, less than 2% in UK!* *want low carbon
- **Electrification –** issues are
  - **cost:** \$ electricity ≈ 3 x \$ gas, so affordability → heat pumps (200-300% efficient)
  - **seasonality** of demand. In UK: replacing gas used in **space & water heating** with electricity + heat pumps would increase average electricity demand by 40% but increase peak/average from 1.5 to 2.0
- Biofuels
- Geothermal
- Solar
- Repurpose gas grid to deliver **green hydrogen**
- ....

Industrial Heat

High T 'process heat' (> 400 C) very hard to decarbonise

17% of all CO2 emissions from cement, iron, steel, and chemical industry



Options for decarbonising process heat limited:

- Green electricity
- Concentrated solar
- Biomass (competition with use in power generation)
- Burn hydrogen (or ammonia)
- ……

Need to re-think industrial processes + capture and store CO2 vented e.g. in cement production and in producing hydrogen by steam methane reforming for use in making ammonia*

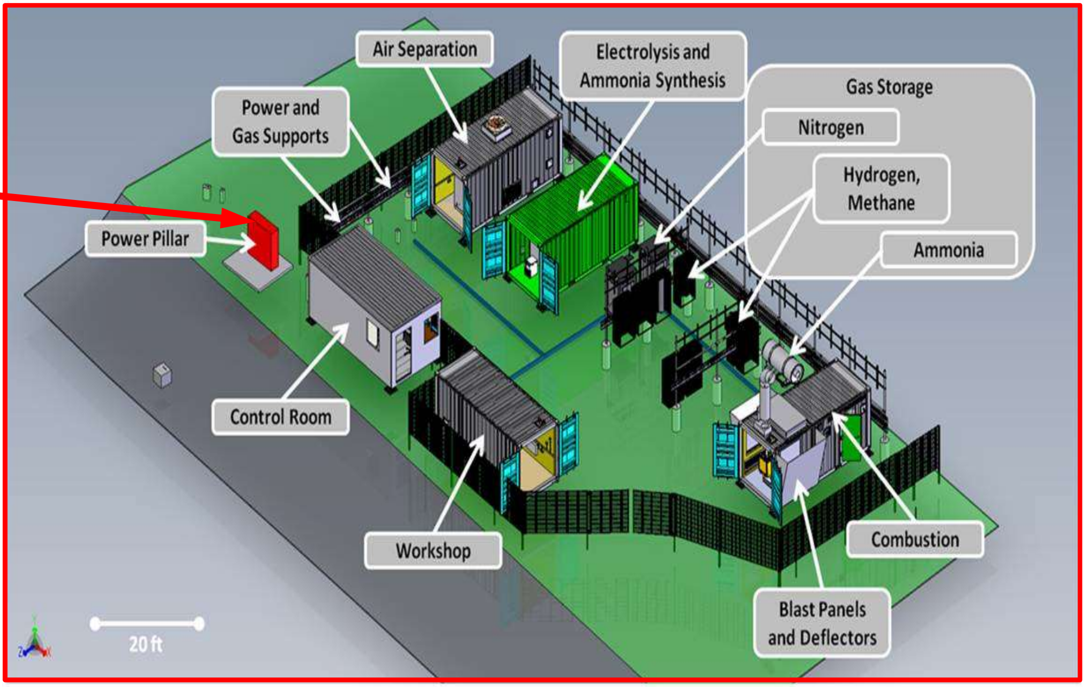
* $90 bn/year market (90% → fertiliser): responsible for 1.8% of world's fossil fuel consumption and CO2 emissions

Example: Green Ammonia

Currently: hydrogen from **S**team **M**ethane **R**eforming of natural gas + Haber-Bosch → ammonia

Alternatives: add CCS to SMR, or → truly **'green hydrogen'** from electrolysis → **'green ammonia'**

0.3 MW proof-of-concept plant
(Siemens, Oxford, Cardiff)
at Rutherford Appleton Lab
Launched June 2018:



- an attractive candidate for power ↔ gas energy storage - much cheaper to transport and store than hydrogen

Huge potential: **c**urrent annual production of ammonia → burned in turbine @ 50% efficiency → all world's power for 7 days

Note: direct electro-chemical synthesis of ammonia from water and air possible although probably not practical – research but chemists should be thinking about such things

Transport

→ **approx. 30% of final energy use and 25% of CO_2 emissions. Energy split**

- **Aviation – 10%:** biofuels, hydrogen, electric??,…
- **Marine – 10%:** LPG, hydrogen, ammonia;…
- **Road – 75%:**

Passenger → 26% of all oil consumption: expect to become electric – batteries, and maybe some hydrogen fuel cells

Freight → 18% of all oil consumption: energy use 50:50 **-** Light Commercial Vehicle: trucks > 15 t

Batteries? Cost/weight prohibitive for heavy trucks? Need

- Greater efficiency (only US, China, Japan and Canada have standards) + change to:
- Natural Gas (combustion) and/or
- Hydrogen fuel cells and/or
- External electric supply: overhead cables, tracks in road,…?

Battery Electric Vehicles

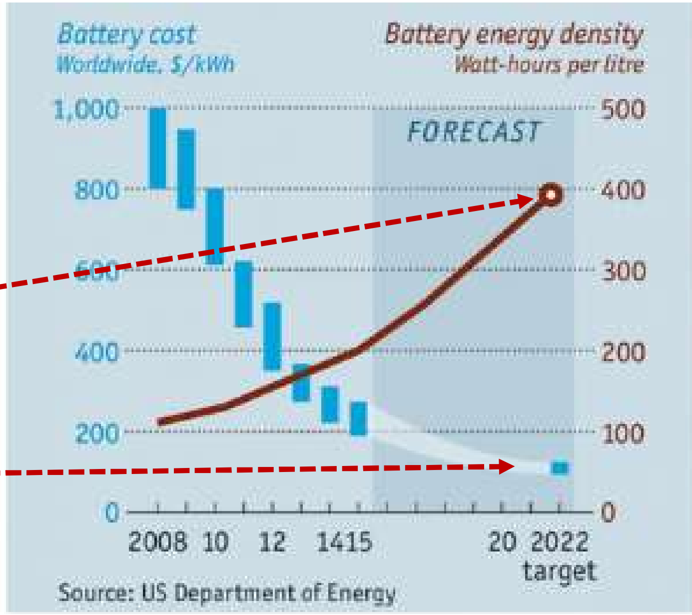
Future numbers of vehicles (1 bn today → 2 bn in 2040?; miles driven), **and mix** (hybrids, plug-in hybrids, pure battery EVs - 1.2 million today: 2040 projections range from 150 million to 650 million) **will depend on**

- **Habits** (car sharing, ride pooling, uptake of other modes - public transport, more teleconferencing, more home working?)
- Uptake of **autonomous vehicles** (need fewer: more efficient, but could put up mileage? 'Dial a car' - hybrid for long distances, battery for short, allowing electrification without range anxiety?)
- **Cost of competition** (internal combustion - twice as efficient by 2040?; hydrogen fuel cells - cost, infrastructure?)

Critical factors for EVs:

Cost* (lifetime cost < ICEs from 2025?), range* and availability of charging infrastructure

*Very dependent on battery cost + storage density
Ambitious targets:
Our colleague P Bruce thinks density may increase 50-60% by 2022



Questions about Battery Electric Vehicles

- **Do they really reduce CO_2?**

  Yes, but currently not radically
  → need to reduce carbon intensity of electricity + energy embedded in batteries
  Likewise for hydrogen fuel cell cars : need to make hydrogen (or other fuel) without C02

- **Is there enough Lithium?**

  Yes (resources are enough for 400 x current annual use - reserves 3.3 times more)
  - near term problem will be expanding production rapidly enough to meet demand
  - long term re-cycling will be necessary

- **Implications for electricity generation and distribution?**

  If all cars in UK → BEVs tomorrow → increase electricity demand by 25% - obviously possible

  Questions – timing*, charging points location (communal/home? UK:43% of homes have no off road parking)/nature (slow, fast, rapid),.....

  * slow charging when cars get home with standard profile → large evening peak: can flatten using an alternative tailored profile (depending on time of year and on day, current state of charge, when vehicle needed,…) provided by smart phone when charging starts

Electricity

IEA	Contribution 2016 Total 24,270 TWh	Increment 2016 to 2040, NPS	Contribution 2040, NPS Total 39,290 TWh
Total	100%	+ 59%	100%
Fossil	65%	+ 22%	50%
Hydro	16%	+ 52%	16%
Nuclear	11%	+ 47%	10%
Wind	3.8% 2017:4.4%	X 4.4	10.9%
Bio & waste	2%	+ 150%	4%
Solar PV	1.3% 2017:1.7%	X 10.4	8%
+ geothermal, concentrating solar, marine – expected to remain small			

Bloomberg
Out of similar total:

29% (Fossil)

24.5% (Wind)

23.5% (Solar PV)

- **Fossils set to remain dominant in near term → Carbon Capture and Storage?**
  - Only captures 80% (whole life cycle). Without a breakthrough, put up cost of power generation by 25+%? Inflexible? No help with pollution. **I doubt it will pay a significant role in power generation**
- **How fast/far can we move to low carbon sources** – hydro, nuclear, wind,…
- **Other issues: diverse sources + new users (cars) – need smarter grid; market reform**

Low Carbon Sources

Are they sufficiently abundant to replace fossil fuels? Yes

Can their costs compete with fossil fuels (would solve the problem)?

Apparently: generation cost for wind and solar now less than gas in good conditions

But

- For 'non-dispatchable' sources cost ≠ value, e.g. if wind blows mainly at night it may be cheap but relatively valueless; if enough is installed to meet average demand, there will be a large surplus at times of high availability of wind and sun/low demand → put up cost at other times
- Cost of integrating wind and solar will increase when their contributions increase: **need i)** very flexible back-up for when wind does not blow & sun does not shine, but it won't be used much → very expensive **ii)** better interconnectors, **iii)** demand side measures, **iv)** storage + *market reforms designed to minimise systems cost*

Area *with good conditions* needed to provide all the world's *current* (thermal equivalent) primary energy (average power 18.5 TW_h or 7 TW_e) **from:**

Biomass
230% of
contiguous USA

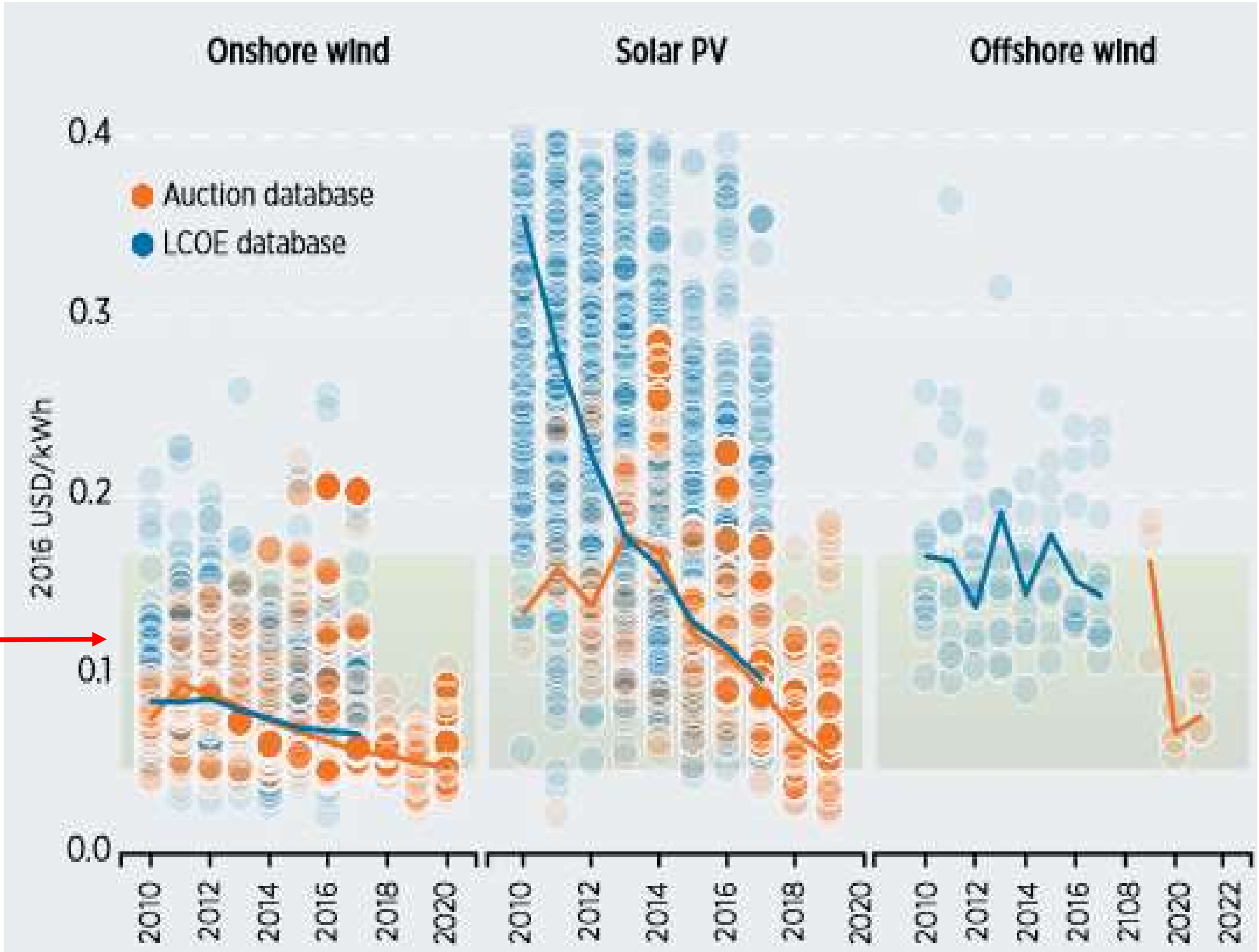
Wind
30% of
contiguous USA

Solar
4% of
contiguous USA

Low Carbon Resources

Contribution 2016 to all energy		**Potential/Area (A) to produce *all* energy**	**Issues**
Biomass + waste	9.2%	A = 230% of contiguous USA in OK conditions	Land & water use, carbon footprint, air pollution
Hydro	6.3%	Could triple	Environmental
Nuclear	4.1%	Unlimited (fast breeders, thorium)	Cost; public perception
Wind	1.5%	A = 30% of contiguous USA in OK conditions	Intermittency On shore: NIMBYism
Solar	0.5%	A = 4% of contiguous USA in OK conditions	Intermittency
Geo	0.1%	Could be important locally (e.g. marine in UK) but not globally	
Marine	0.001%		

Electricity Generating Costs (IRENA)



Hinckley C

Energy Technology Institute thinks cost could be reduced – to around 0.06?

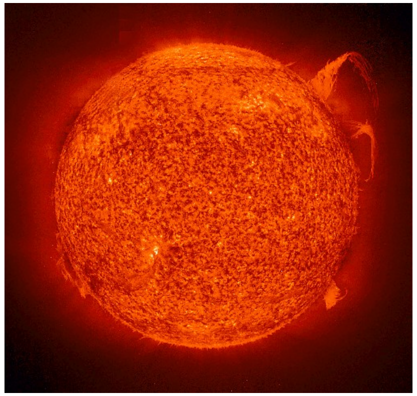
Fossil fuels

Intermittent → *value less than cost*

Remarks on individual low carbon Sources 1

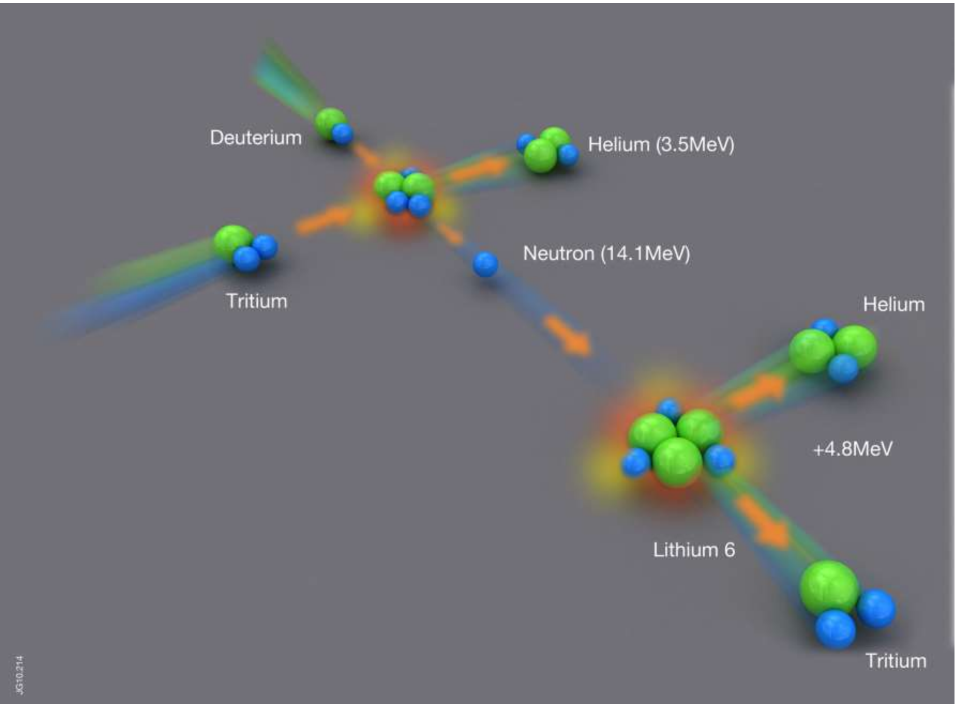
- **Bioenergy -** potential big increase ***if*** CAM plants (prickly pear, euphobia, ..) which need little water can be exploited *and* anaerobic digestion can be speeded up (imitating ruminants)
  Lot of talk about BECCS (bio + Carbon Capture and Storage – carbon negative) – action?
- **Hydro –** expect + 50% or more by 2050
- **Nuclear** – issues:
  - Uranium? Plenty - over 250 years with current use (then thorium, fast breeders)
  - Public perceptions
  - Cost + financing are the real barriers: would **S**mall **M**odular **R**eactors be cheaper?
  - Inflexibility: don't understand lack of interest in adding of thermal storage – reactor in steady state, producing heat to be stored and then used to deliver power when needed (or heat → housing, industry)

Can we get useful energy from Nuclear Fusion which powers the sun and stars?

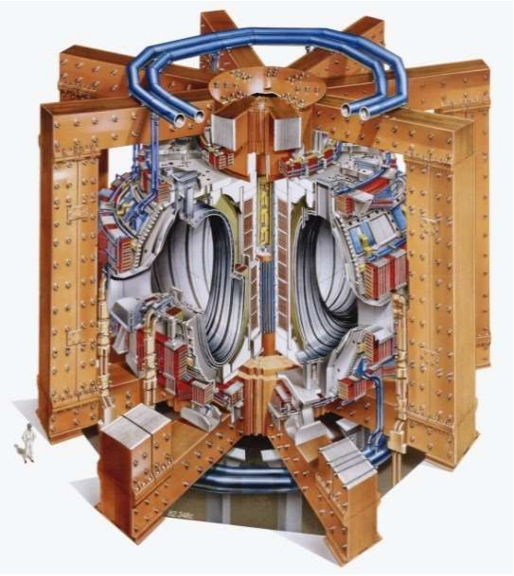


Fusion energy is released when two light nuclei merge

The most promising fusion reaction for producing energy on earth is:



A controlled 'magnetic confinement' fusion experiment at the Joint European Torus has (briefly) produced 16 MW of fusion power from the D-T reaction, so it seems the answer is yes



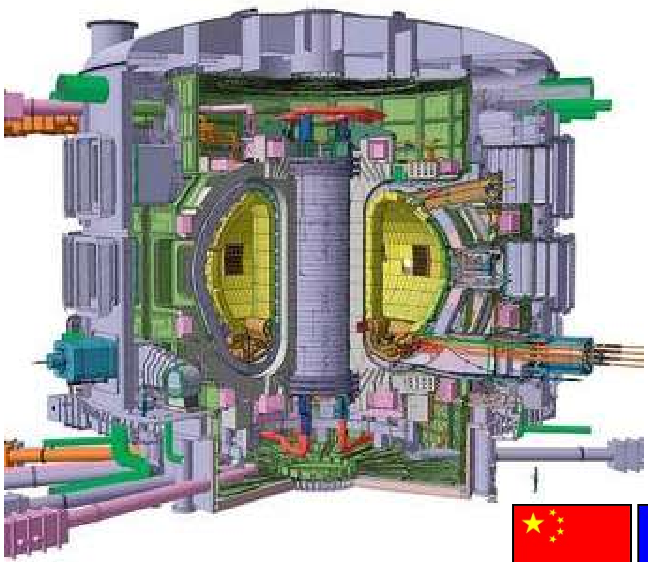
Many attractions (unlimited fuel, relatively safe, low carbon) but not clear if it can be done reliably and economically on the scale of a power station

Questions

- **Could we make a fusion power station?** Probably yes, but very challenging:

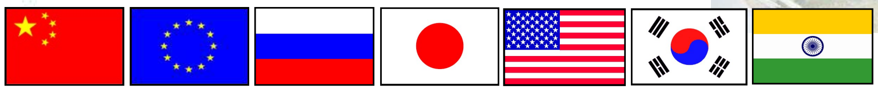
  need to heat ≥ 2000 m^3 of dilute gas to 150 million ^{0}C and keep it away from the walls for weeks (JET ~ 80 m^3, seconds). Cannot be demonstrated on a small scale.

  To be sure (e.g. that there are no new instabilities) **need to study burning plasmas in**



ITER

Global fusion project under construction in Provence



- **Could we make it: reliable?** Not clear, but technology moves on… **Competitive?**

Cost of fusion:

15 years ago, cost estimates suggested that fusion could compete with other low carbon sources, but since then:

- **Cost of wind and solar decreased** faster than anyone imagined possible
- **Cost of ITER way over budget**: way it's set up, management issues, unique FOAK,… but also *costs greatly underestimated*

Need to finish ITER (alas DT now not expected until 2035) **to show that we really can make a fusion power station**

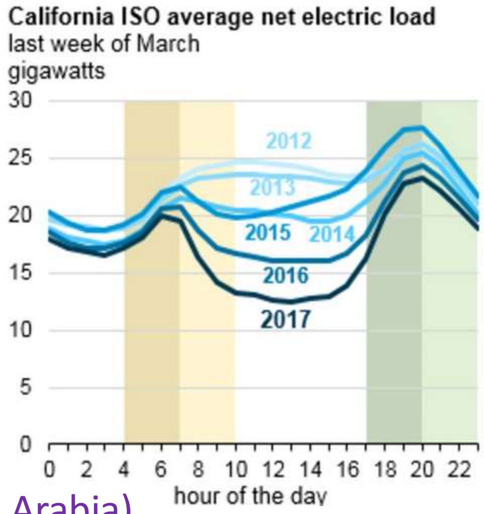
and then **re-assess costs before deciding whether to proceed to build ITER-like Demonstrator Power station**

Meanwhile need to

- improve understanding (and control of) of turbulence in fusion plasmas to see whether we can reduce transport of heat to the walls, and 'confine' plasmas in much smaller (hence cheaper) devices. Regions with little turbulence (not understood) give some reason to hope. And
- continue to explore smaller (more efficient) configurations, e.g. 'spherical tokamak' pioneered at Culham

Remarks on individual low carbon Sources 2

- **Wind**
  - Cost still falling (especially impressive for offshore, where size is increasing - 12 MW turbines under development: 15 MW by 2025?) and capacity factors growing
  - First floating wind farm 5 x 6 MW 30 km off Scotland. Statoil 'ambition' 40-60 €/MWh by 2030. Opens up big new potential (should look for areas with uncorrelated wind resources)



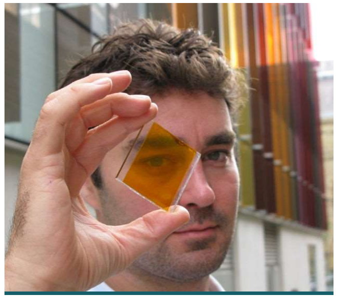
- **Solar**
  - Success → danger that solar will 'eat its own lunch' where resource is good, e.g. in S California
  - Cost of balance of plant > cost of modules → even greater premium on efficiency (Oxford PV just announced lab result of 27.3% for Perovskite-Si tandem)

Lots of good news (wind $18/MWh in Mexico, solar $17/MWh in Saudi Arabia)

But a long way to go, fossil fuels still ~ 80%, **and**

- Cost of integrating solar & wind will rise as their contributions increase
- Electricity markets will have to be re-designed to deliver optimal solution

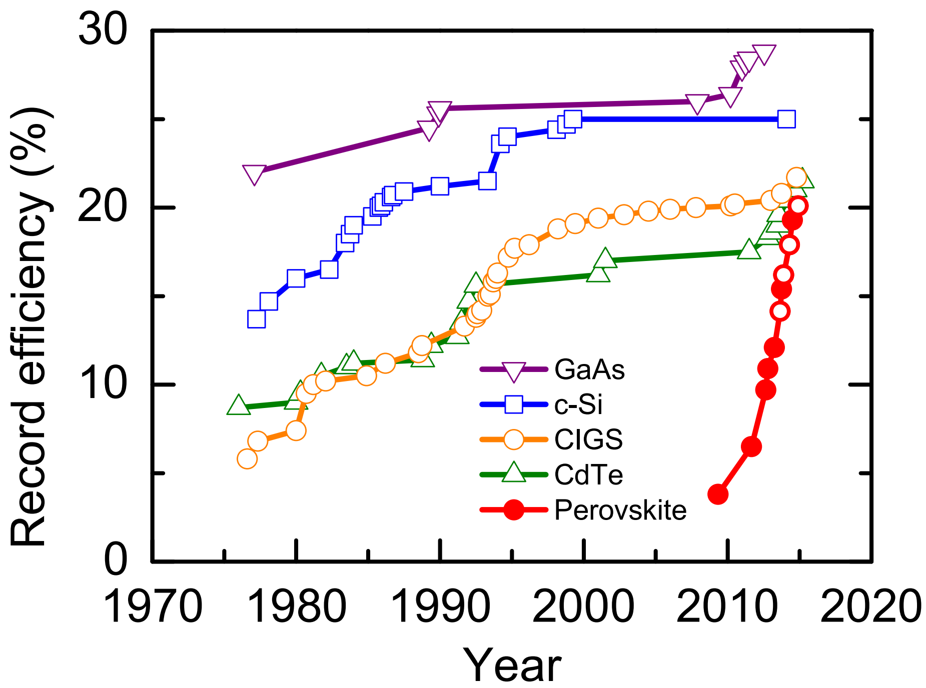
Solar Cells Incorporating Perovskites



Pioneered by Henry Snaith - one of '10 people who matter' according to Nature, Dec. 2013

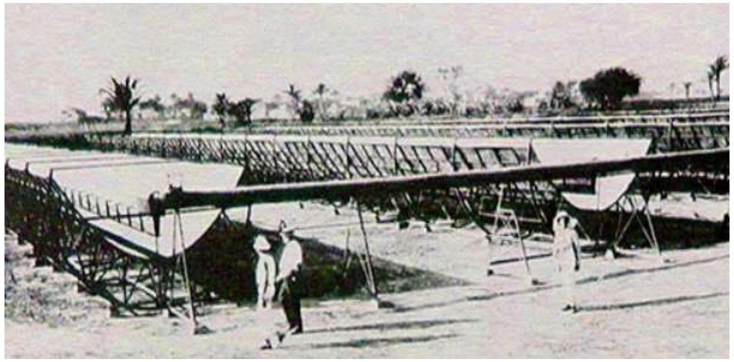
Meteoric rise in efficiency:

Initial focus on low cost of perovskites as a cheap alternative to Si, but Si got much cheaper. Now focusing on tandem cells .By combining perovskite cells with a 19%-efficient silicon cell, have reached 27.3% efficiency



Concentrated Solar Power

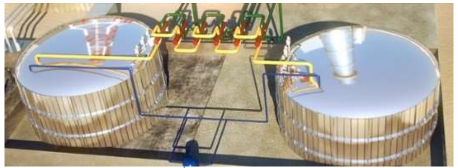
First example:
Schuman's 100 Horse Power (74 kW) Solar Engine One 1916, at Al Meadi near Cairo:



Today

Various configurations

Some work at very high temperature

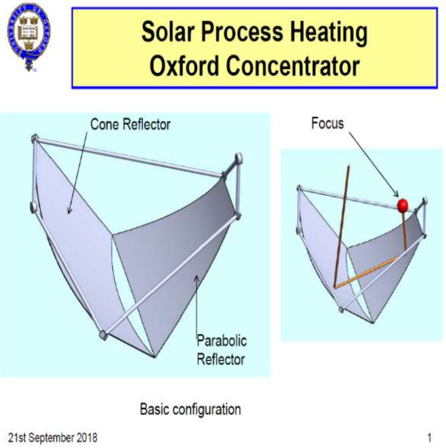


can store some of the heat during the day in molten salts:
→ generate electricity at night

In 2017 PV provided 30 x energy obtained from Concentrating Solar Power, but it will probably have a role, coupled with thermal storage or in other applications

Oxford Solar Concentrator

spun out from the solar neutrino experiment that won the 2015 Nobel Prize for physics



Replaces parabolic mirror (expensive to manufacture) with reflection from two much cheaper mirrors (cone + parabola) which produce the same effect

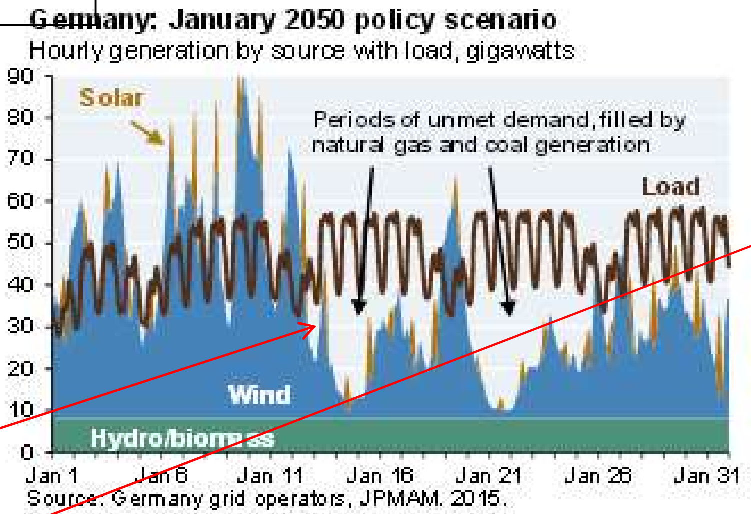
Could be used in sunny countries e.g. to melt aluminium scrap for re-cycling

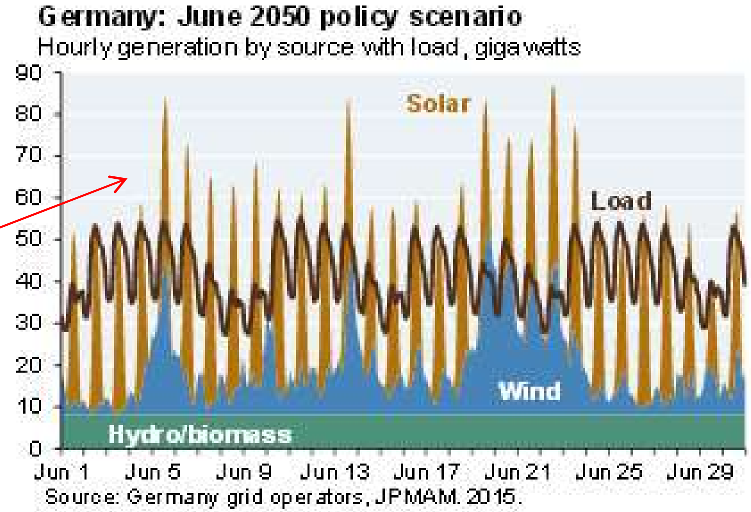
or as basis for a Solar cooker , being trialled in Tanzania for day-time cooking + sterilizing water → reduce deaths from air pollution + save money

Integrating renewables

Model of power in Germany in 2050:

Assumes demand - 25%, wind x 3, solar x 2





To fill deficit/absorb surplus need mixture of

- Very flexible back-up
- Aggressive demand management
- Smarter/larger grid (better interconnectors)
- Storage (solar – batteries OK; wind – need days: ideally seasonal)

(This model is expensive: adding significant nuclear → large cost reduction)

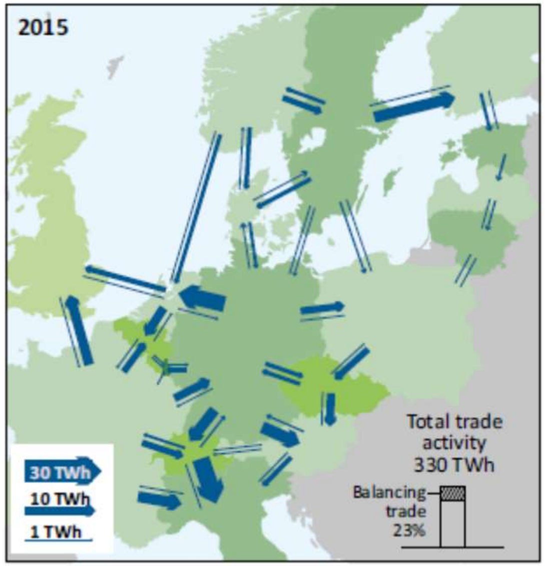
Must be complemented by understanding how to attribute and charge for benefits of storage & improved grid, and **Market reform** – incentives/business models to deliver what's wanted (little used back-up,…)

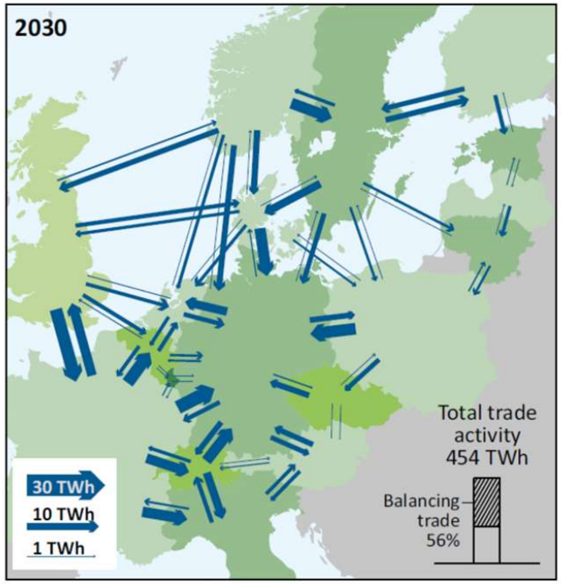
With these measures can move to large amounts of wind and solar – although very hard to get to zero fossil fuels without large-scale long-term storage (power → gas?)

Supergrid Happening in China

lines under construction in India, Brazil, USA,…

But not in Europe where it could lower cost of solar/wind in Germany by bringing power from the south/west of the continent, link to storage capacity in Scandinavia….

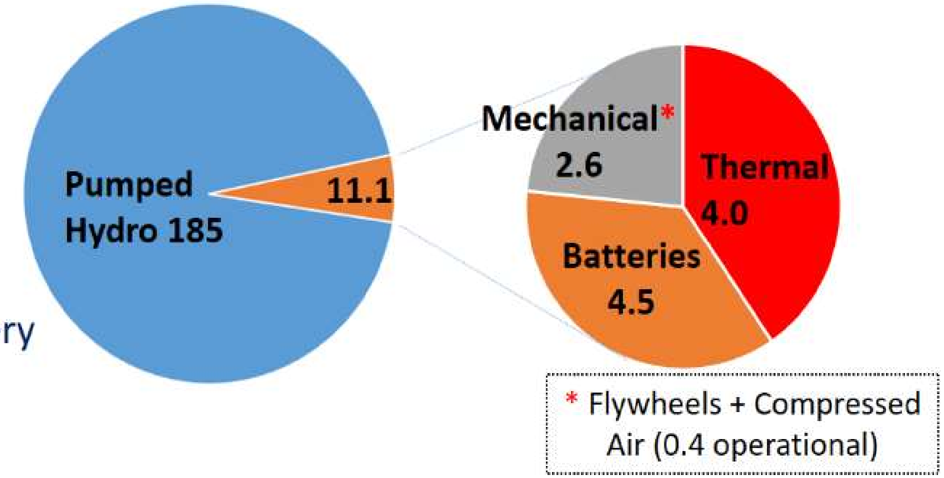




Grid Scale Storage

Current global capacity in GW:

DOE global energy storage data base
(may include some projects not yet operational)
Volume (some 1 TWh) not easily available
Batteries growing rapidly, but still small
Dinorwig can store 9 GWh = 70 x S Australia Tesla battery



Future:

<u>**Local**</u> – **Li-ion batteries**; heat (UK domestic hot water tanks store ~ 40 GWh)

<u>**Central**</u> - **Li-ion batteries** (try to use electric vehicles); compressed air; **flow batteries**; more pumped hydro; **heat**/cold; **power to gas** (ammonia or hydrogen) **if affordable will be very important**

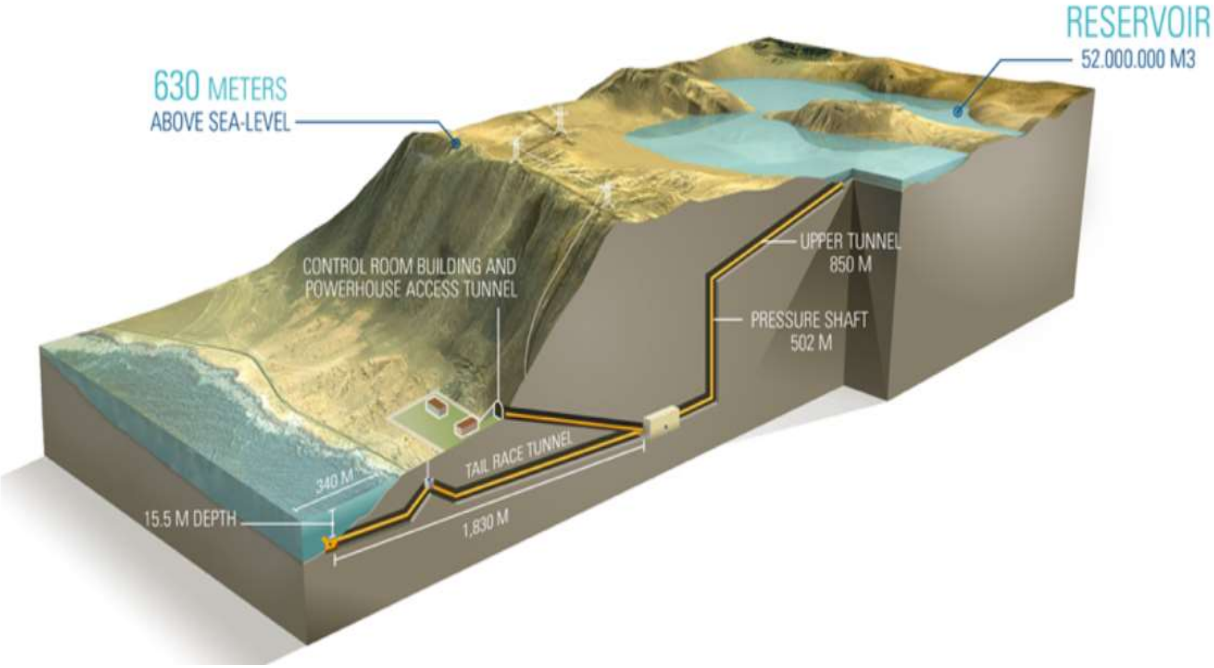
Need to understand: scalability; cost; efficiency; value of benefits (grid services, less back-up, use all wind & solar, arbitrage,…); how to charge beneficiaries (part of generation or transmission?); how to incentivise provision,….

Two interesting storage projects

Tesla battery plant S Australia

100 MW/129 MWh cells made within 2 months

600 MW solar PV + 300 MW pumped hydro project Espejo de Tarapaca, Chile



Issues for Electricity Markets

Underlying problems: supply and demand must match instantaneously; a rapidly changing environment (distributed supply, new loads – electric cars, environmental targets, …); marginal cost of wind and solar is zero; security of supply considered a public good;……

Different incentives/subsidies/regulations in different countries/states – market distortions, unintended consequences….

Issues include:

- **How to ensure sufficient capacity to meet maximum demand** (last kWh = by far the most expensive)**?** Capacity markets in many countries – risk aversion → over procurement? Bias towards incumbents. Unexpected outcomes?
- **How to ensure sufficient conventional generation** - being displaced by zero marginal cost renewables when the wind blows/sun shines, undermining business case (German utilities facing bankruptcy)? Movement from subsidising renewables to subsidising back-up
- **How to assess who benefits, and how they should pay**, for strengthening the grid, storage?
- **Who should provide storage** (generators, distributors, others), and **how should provision be incentivized?** Value that can be captured (arbitrage, balancing) < value to the system
- **How to implement a systems approach to demand management, storage and strengthening the grid?**

Can We Meet the Paris Goals?

There is some good news (following slides) **but** most needs qualification

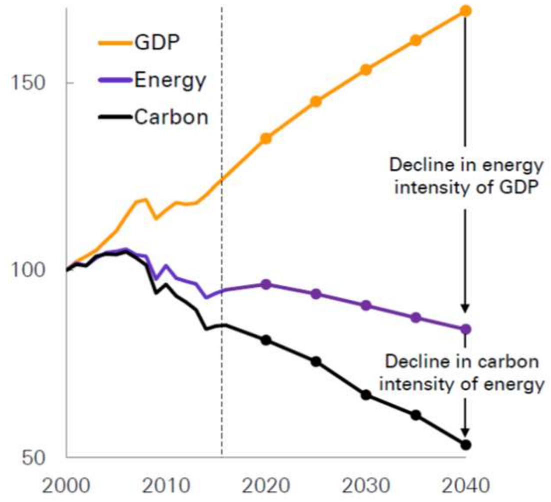
Will need most or all of:

- Continued fall of cost of wind and solar: necessary but not sufficient given intermittency
- Continued fall in cost + improvement in performance of batteries→ electric vehicles; day/night storage of solar; frequency/voltage control of grid;…
- Development of affordable 'green' hydrogen and/or ammonia → long-term storage; process heat; space heat; …
- Continued improvements in efficiency (regulation)
- Support from more (pumped) hydro; cheaper nuclear (if possible flexible),…..
- **Negative emissions to compensate for stubborn sectors (aviation, shipping, cement manufacture, some chemical processes, glass manufacture,…) & recalcitrant nations – looks essential**
- Good policies (including a carbon price)
- **Social acceptance/political will**
- ….

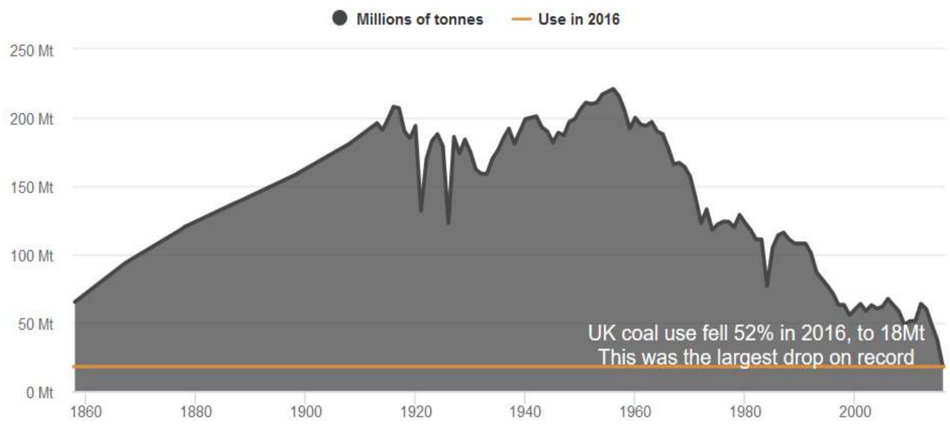
Necessary to push for all these, and hope for 'Black Swans'

Qualified good news 1

Energy consumption, carbon emissions and coal consumption are falling in OECD countries, particularly the **EU**:

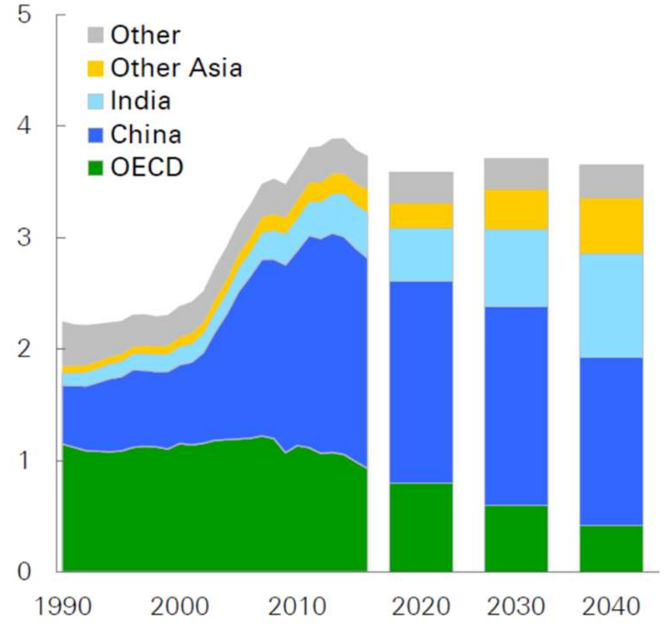


BP 2018



UK Coal Use (Carbon Brief 2017)

But global coal consumption is plateauing, not falling (falling in China):

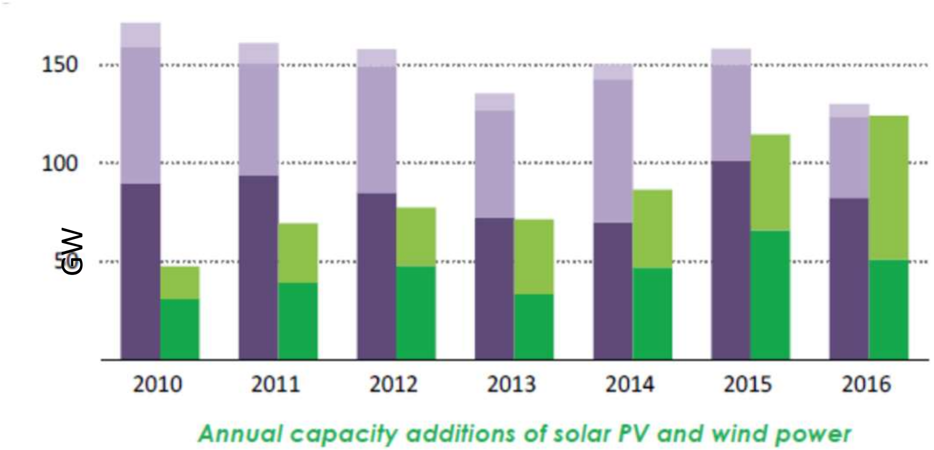


BP 2018

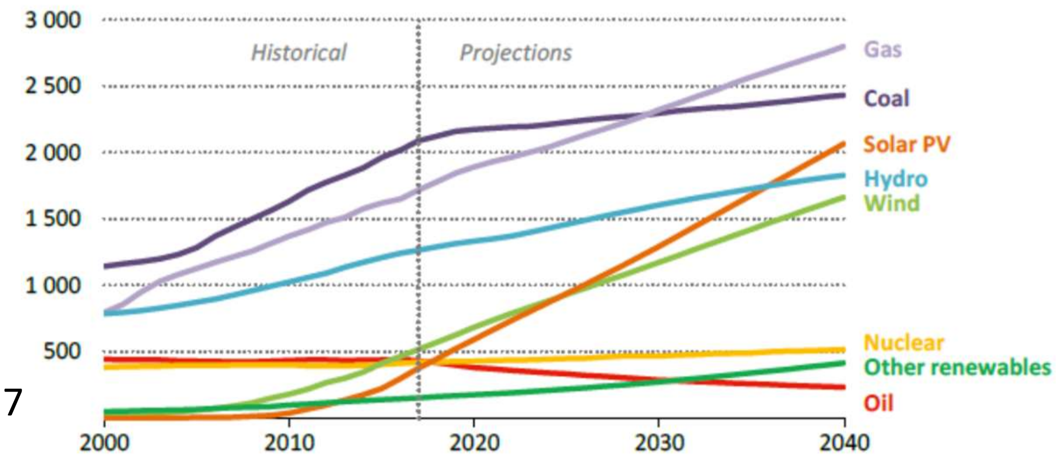
oil consumption not expected to plateau until 2030 and gas looks set to continue rising at 1.6% over next two decades

Qualified good news 2

The costs of renewables and batteries are falling and **installation [installed] capacity of wind and solar are overtaking [catching up] coal and gas:**



IEA 2017



But for intermittents cost ≠ value, **capacity factors** [output/(max 24 hour output)] **are low:**

solar – 12.6%, wind 24.9%, hydro – 38%, coal - 53%, nuclear 72%, gas 40%

and **their contributions to total electricity generation are still small**

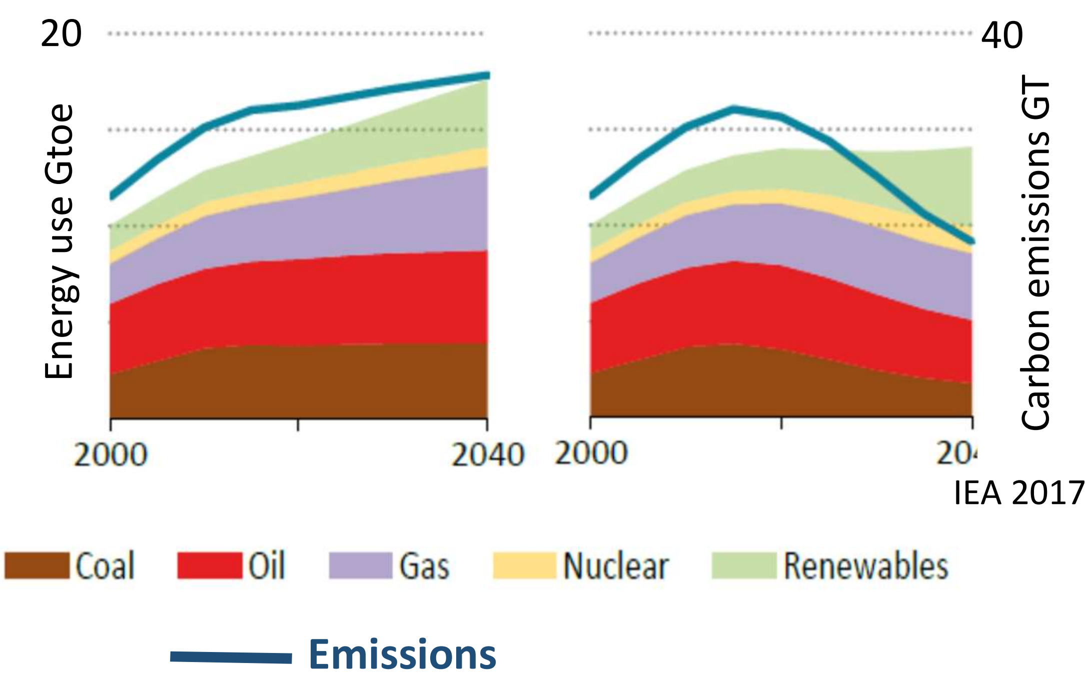
solar – 1.7%, wind – 4.4%, nuclear – 10.3%, hydro – 15.9%, gas – 23.1%, coal – 38.1%

Qualified good news 3

Although ‘realistic’ projections show growth of carbon emissions slowing but not stopping:

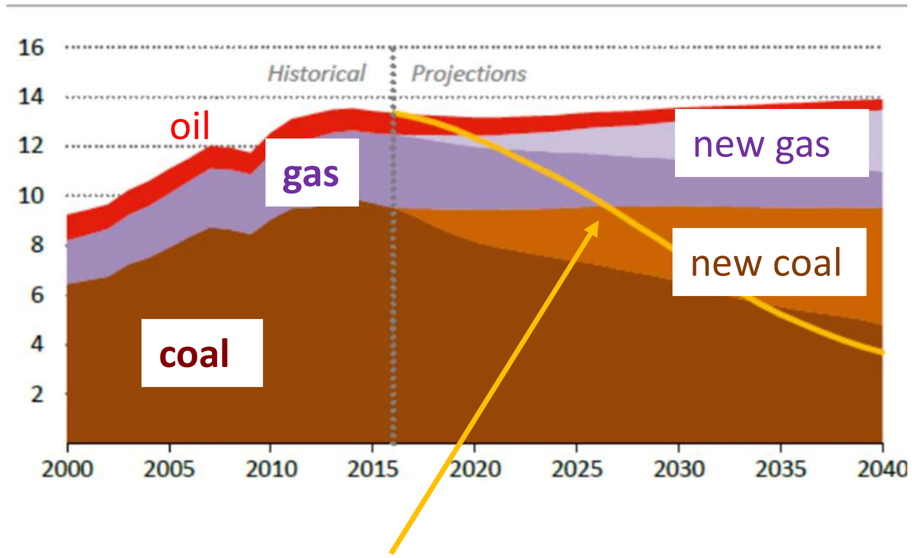
There are projections in which emissions fall (and Paris targets are met):

New Policies **Sustainable Development**



But all are extremely challenging, and some are impractical:

Global power sector CO_2 emissions by fuel in the New Policies Scenario



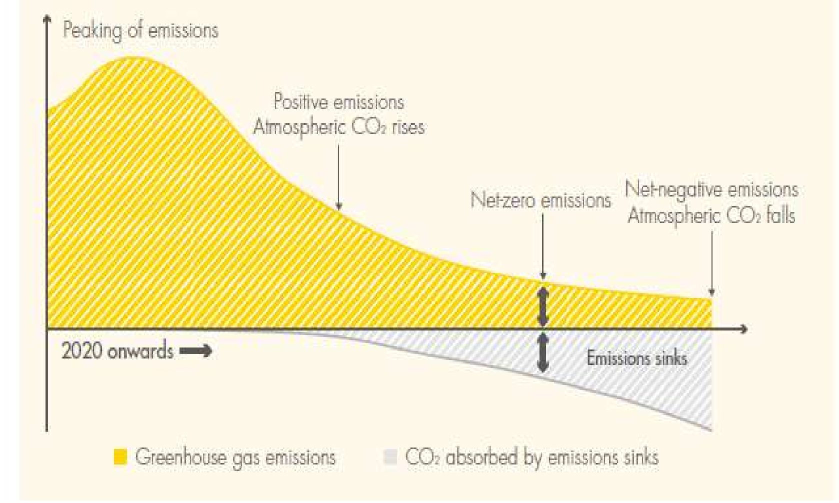
Sustainable development scenario only possible if all construction stops and some existing power plants are closed prematurely

Negative Emissions of order 10 Gt CO2 p.a. required in scenarios that meet the Paris goals

- **to deal** with stubborn/irreducible emissions (air travel, agriculture, parts of industry, …)
- **From** a/reforestation, changed land management, BECCS (bio-energy with CCS), enhanced weathering, direct air capture*, ocean fertilisation,…

e.g. Shell's Sky Scenario (which pushes boundaries in every area but is not inconceivable) **requires 11.9 Gt CO2 sequestered pa (2.6 at source),**

- and even then has +1.8 C in 2100



* **Carbon Engineering/David Keith** (Harvard) have recently claimed, using data from their pilot plant, that the levelised cost per tonne of CO2 captured by a full scale direct air capture plant would be $(94-232) – exciting!

Pilot plant

Commercial scale reference design
→ somewhat under 1 million t CO2 p.a.

Concluding Remarks

- Meeting the Paris goals will be extremely difficult, but not impossible (benefits as well as costs - but they won't accrue in the same places)
- There is a very long way to go (still at nearly 80% fossil fuels)
- In the near future the route is clear (anything that will be deployed at scale in the next 20 years is presumably already proven and available) – more wind and solar, electrification of transport, greater efficiency,…
- In the longer term it's less clear: renaissance of (cheaper) nuclear? Long-term storage enabling almost 100% renewables? Relatively inexpensive negative emissions?.....
- Whether we succeed will depend on political will as well as technical developments, which now have a momentum that may soon take us to a tipping point

Tipping points can occur and I can imagine a world mainly powered by (over-provision) of cheap wind and solar, supported by storage (which is attracting a lot of effort) and maybe cheaper/dispatchable nuclear

Past Tipping Point

New York 1900

New York 1913