Fusion in the future mix of energy production

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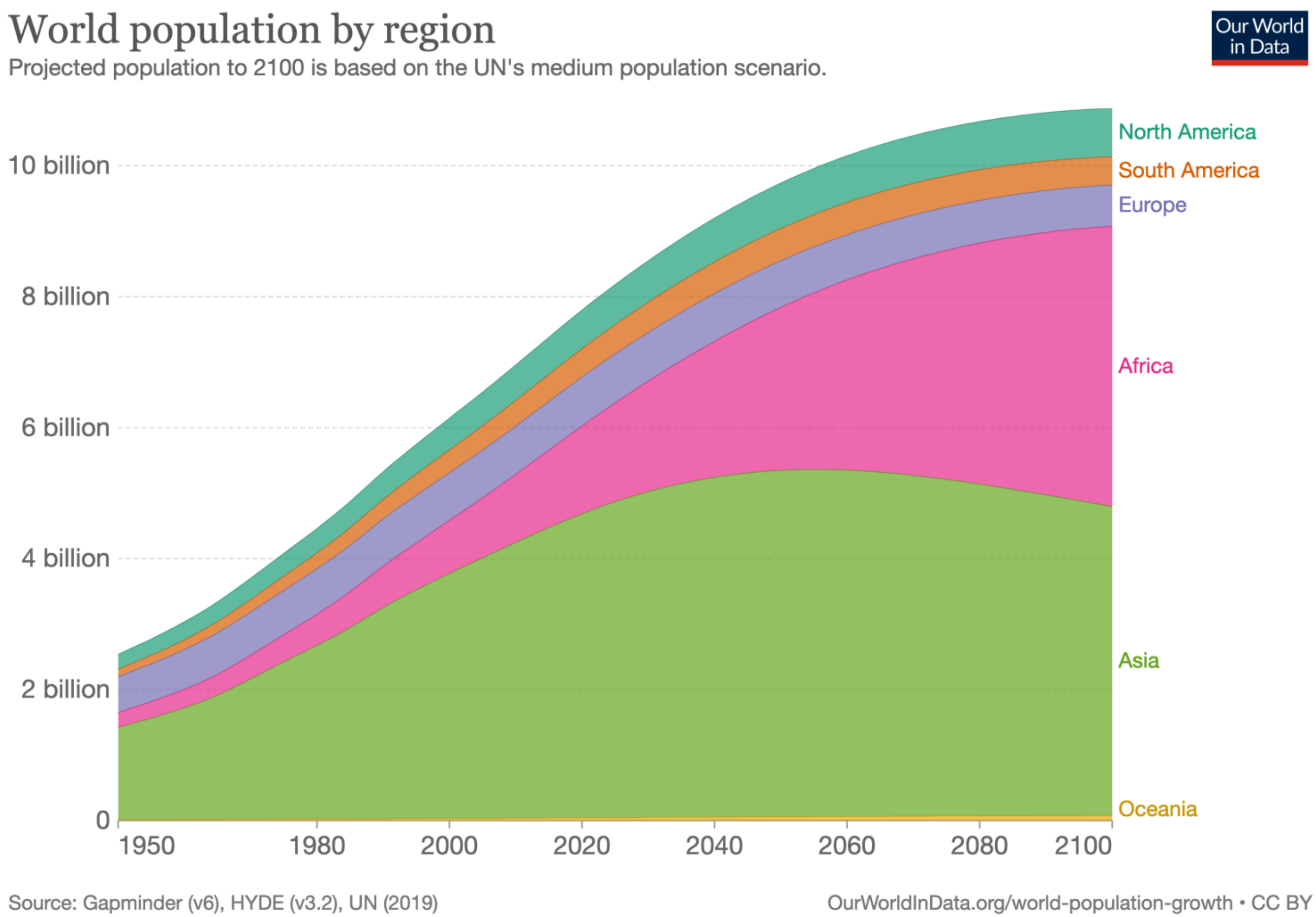
Outline

- (Why) do we need fusion?
- Energy market penetration – lesson from other technologies
- Limitations of deployment

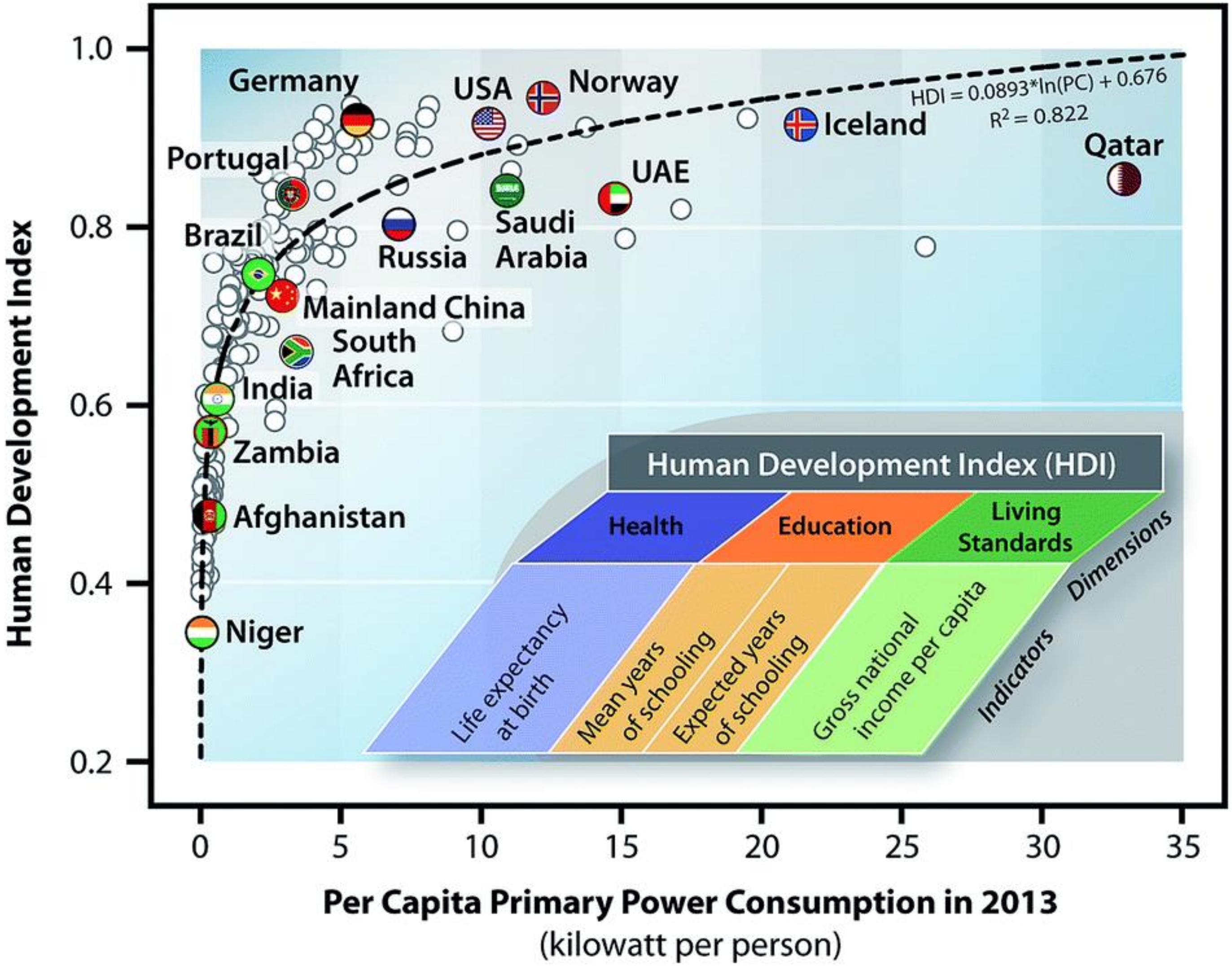
Mankind energy usage

World's population is projected to increase to 11 billion by 2100, predominately in Asia and Africa



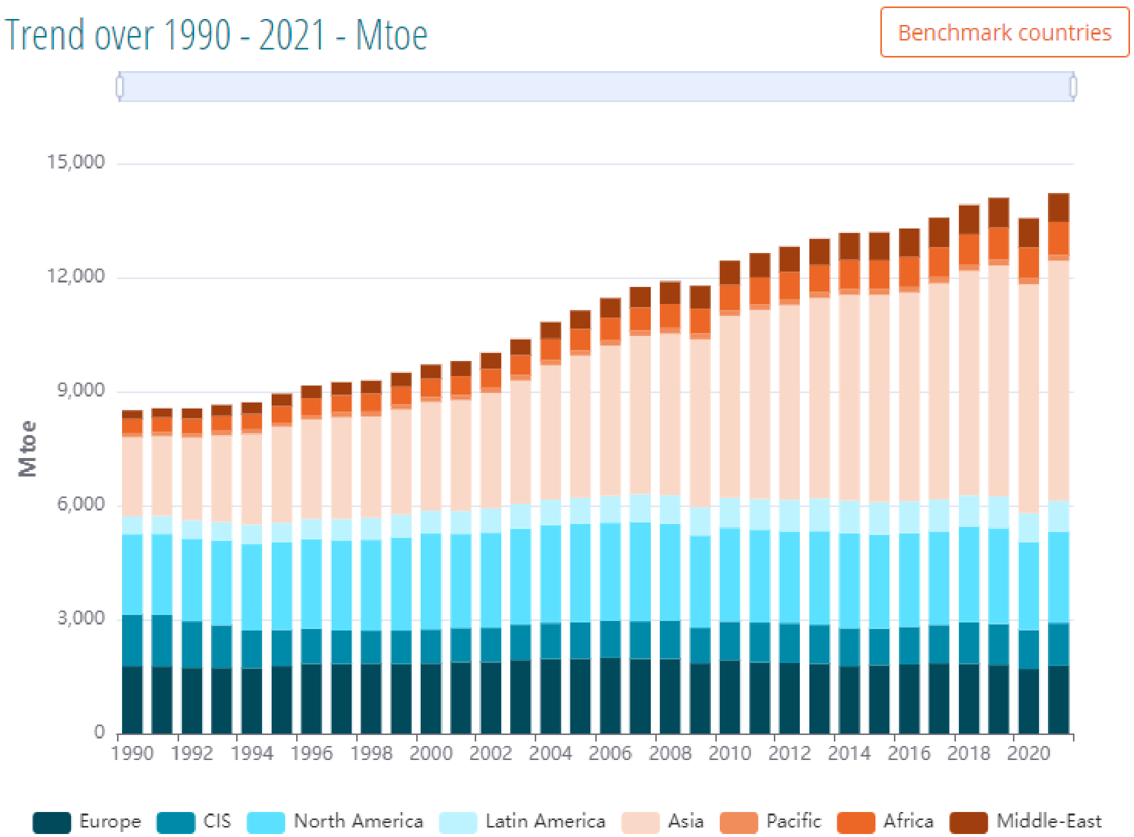
Moore et al., 2019

Energy (electricity) consumption increases with human development



Dale et al., Royal Chemical Society of Chemistry 2013

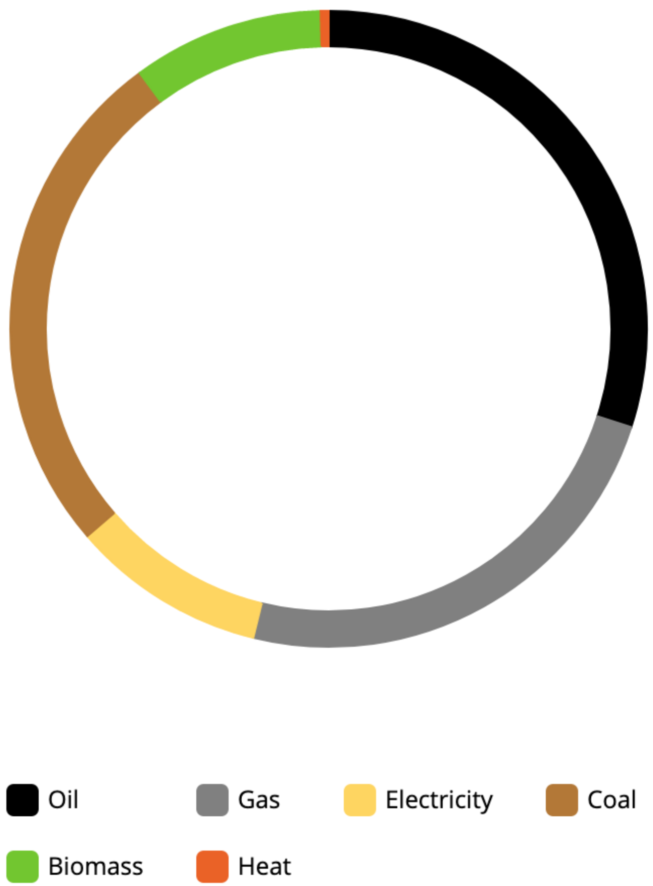
World energy consumption has been and is continuously increasing



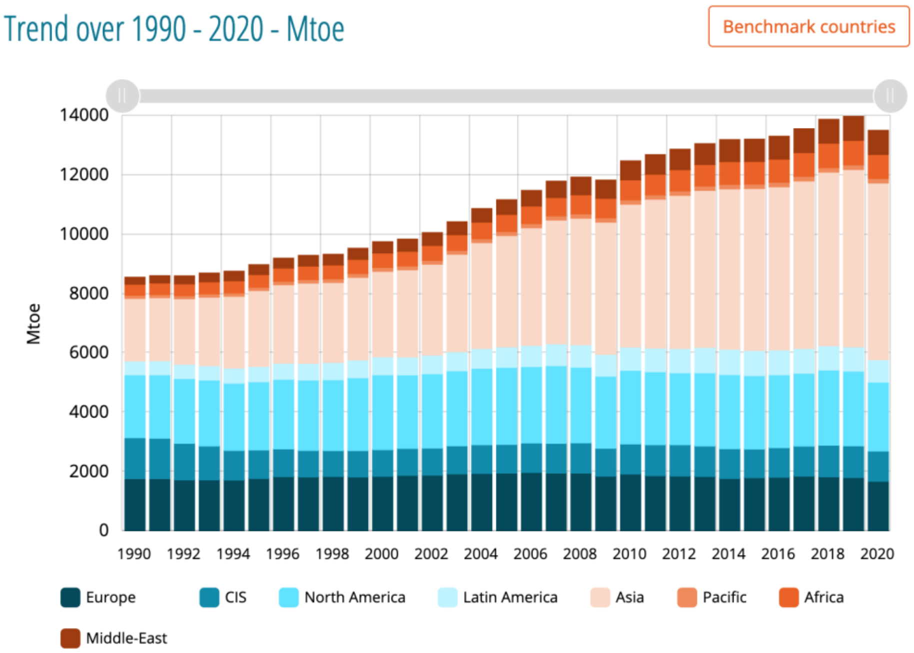
https://yearbook.enerdata.net

Consumed energy primarily from fossil fuels: oil, gas and coal

Breakdown by energy (2020) - Mtoe

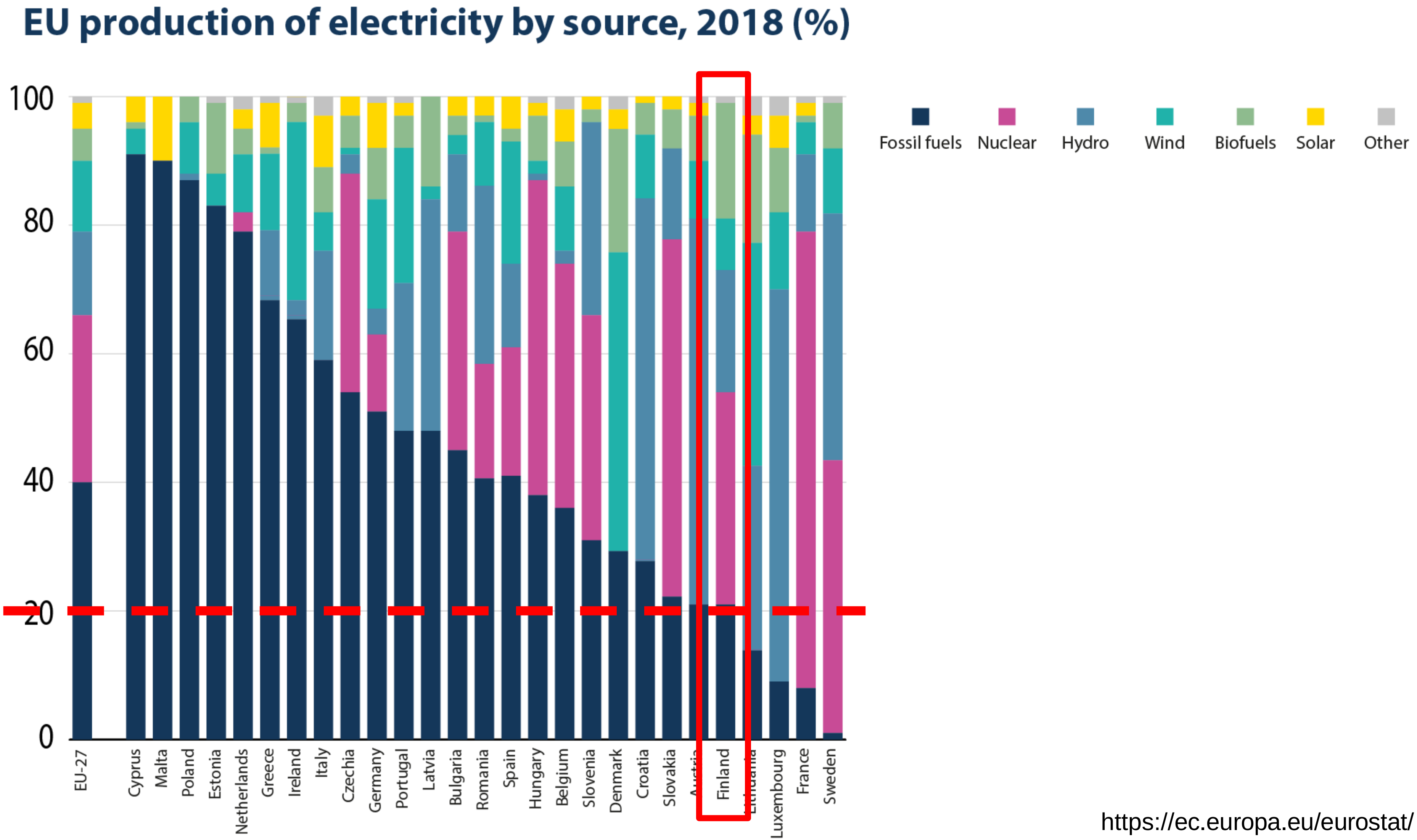


Trend over 1990 - 2020 - Mtoe



https://yearbook.enerdata.net

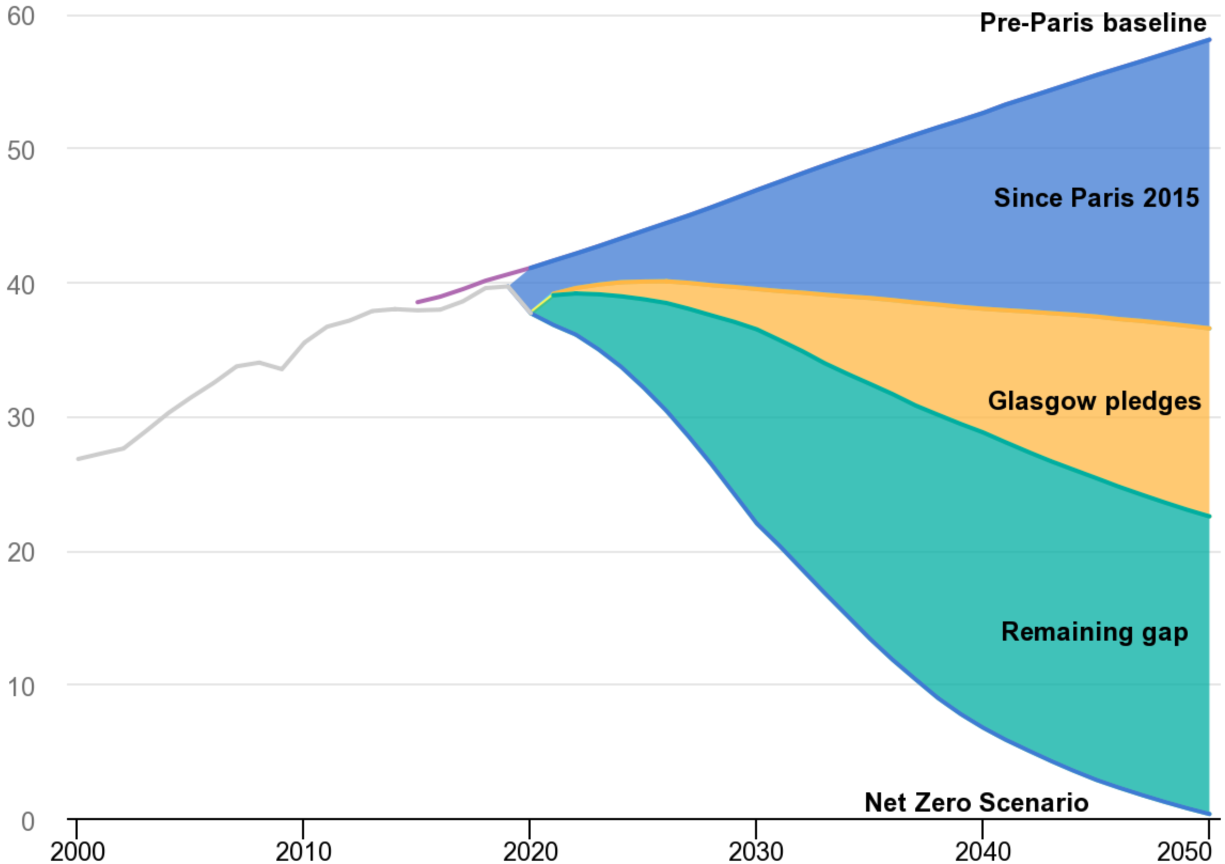
Total primary energy supply for EU member states: Finland's consumption still dominated by fossil fuels



https://ec.europa.eu/eurostat/

How/can we meet the Paris and Glasgow pledges to reduce the CO_2 emission globally?

Global CO2 emissions (GtCO2-eq) **by scenario, 2000-2050**



IEA – World Energy Outlook 2021 https://www.iea.org/reports/world-energy-outlook-2021/executive-summary

Present primary energy sources and their drawbacks

- **Fossil fuels (coal, natural gas, petroleum): depleting resources (≈ 200, 60, 40 years) ⇒ CO_2 pollution, global warming**
  - Oil and gas are local sources ⇒ political and military conflicts
- **Fission: public acceptance, proliferation, waste, Chernobyl/Fukushima-type accidents**
- **Solar and wind: low energy density (to power large industrial installations and cities), storage, distribution and availability**

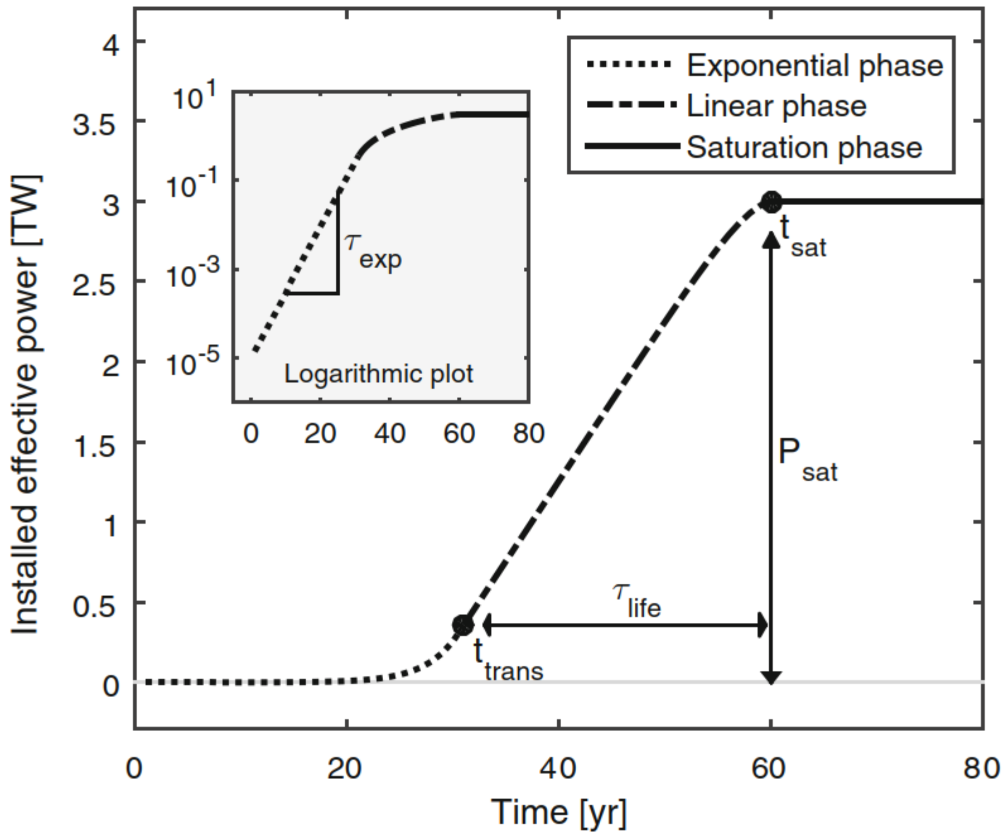
⇒ **Development of any new energy sources at industrial level has a lead time of at least one decade**

Benefits of fusion

- **Fusion fuels are abundantly available**
- **Efficient energy source:** only small amounts (grams) of hydrogen isotopes necessary ⇒ 250 kg of fuel per year (c.f., coal plant 2.7 million tons)
- **Energy output at GW level**
- **Process is inherently safe:** no run-away process (plasma will quench)
- **No pollution or greenhouse gas production, no immediate radioactive waste:** reaction product (helium) is an inert, non-toxic gas
- **No proliferation, low activation of materials**

The growth model of new energy sources

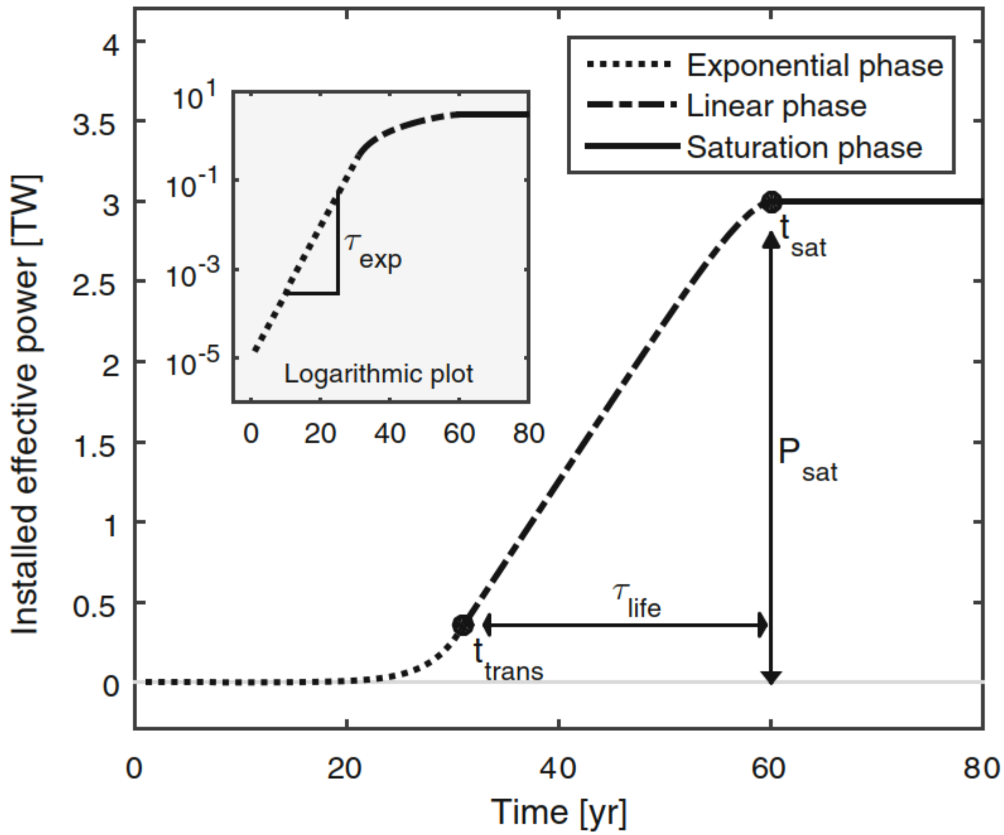
Energy systems typically has long lifetimes ~30 years with expected doubling time ~ 3-4 years



- **Development starts exponentially until transition to linear growth (demand=production capacity)**
- **Saturation at significant fraction of energy production (10%) ~ 3 TW**

Lopes Cardozo, N. J., A. G. G. Lange, and G. J. Kramer. “Fusion: Expensive and Taking Forever?” *Journal of Fusion Energy* 35, no. 1 (February 2016): 94–101. https://doi.org/10.1007/s10894-015-0012-7.

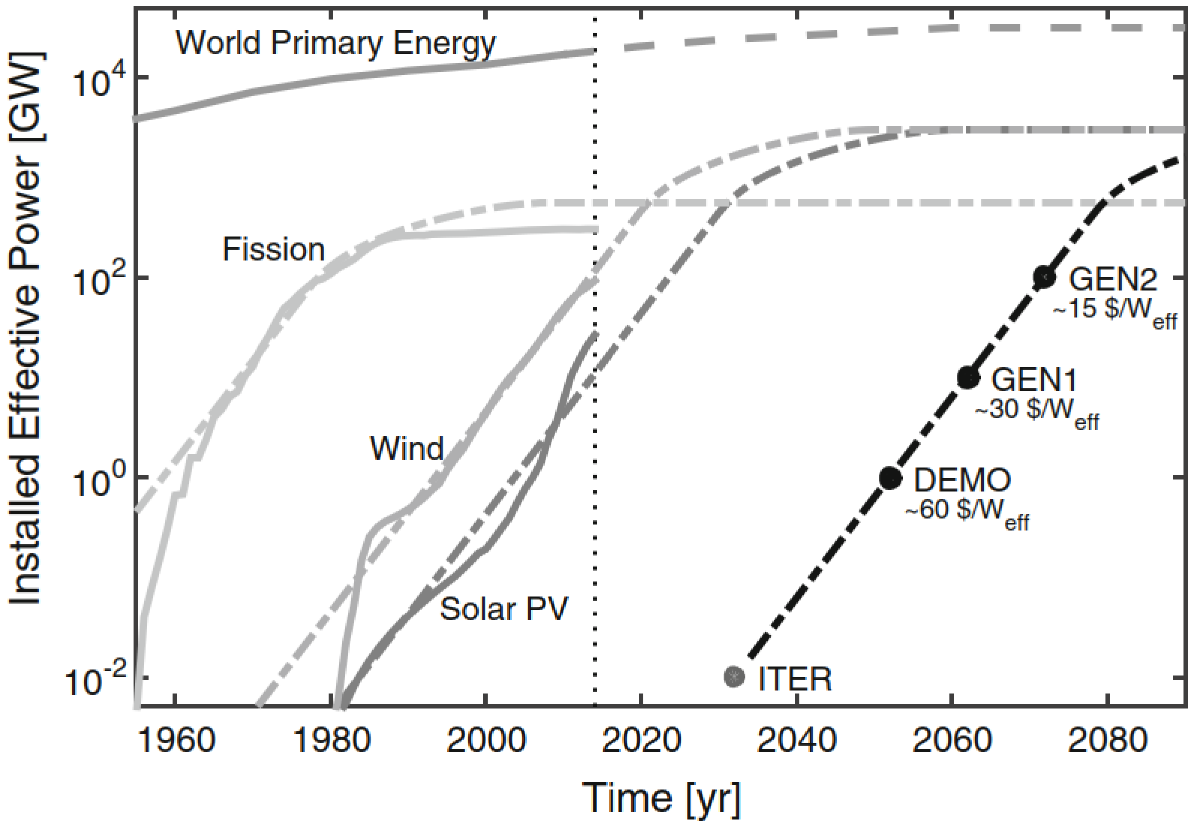
Most installed capacity realized at the end of the exp. Phase → production of several years



In the exponential phase, there is no net energy production!

Lopes Cardozo, N. J., A. G. G. Lange, and G. J. Kramer. "Fusion: Expensive and Taking Forever?" *Journal of Fusion Energy* 35, no. 1 (February 2016): 94–101. https://doi.org/10.1007/s10894-015-0012-7.

Historical data shows generality across different technologies



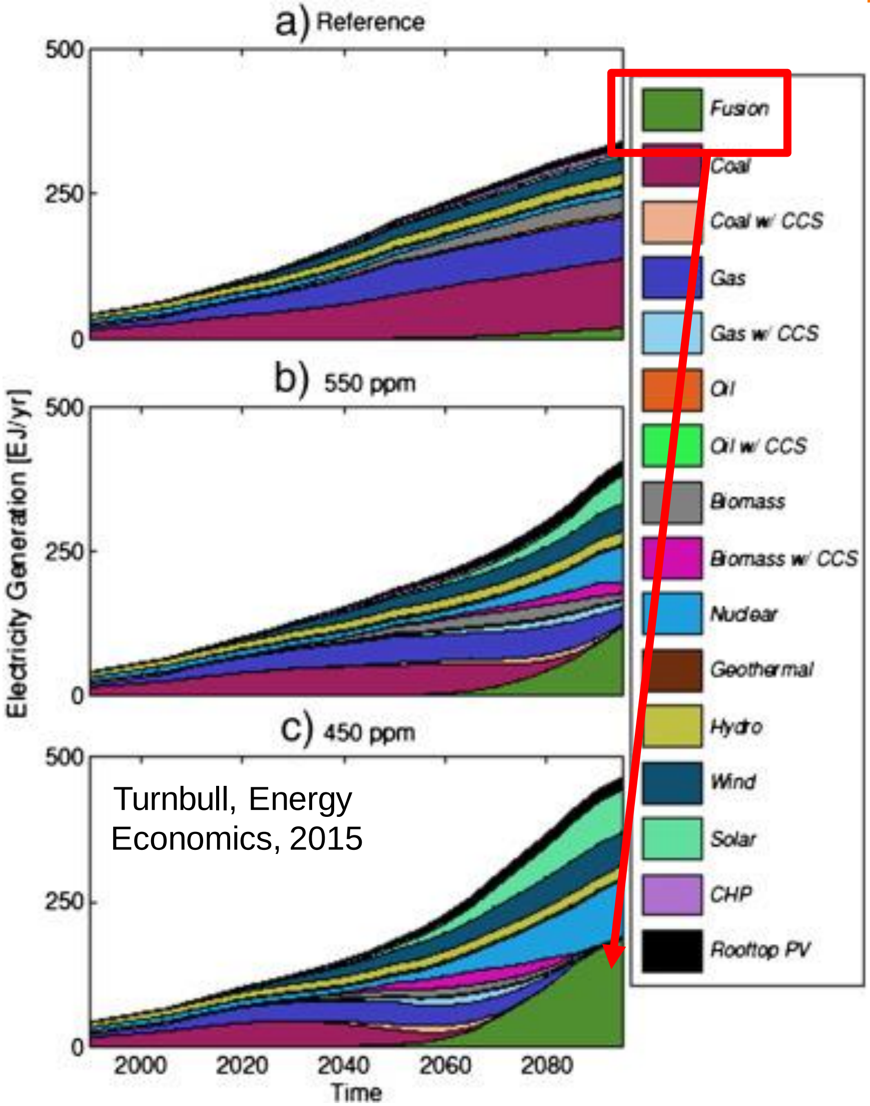
- **Transition phase (materiality) at 1% global capacity ~ 0.3 TW ~ 2 T$**
- **5 B$ in private funding, ~50B $ ITER**

Fusion is late for net-zero scenario, may exist post-transition

Lopes Cardozo, N. J., A. G. G. Lange, and G. J. Kramer. “Fusion: Expensive and Taking Forever?” *Journal of Fusion Energy* 35, no. 1 (February 2016): 94–101. https://doi.org/10.1007/s10894-015-0012-7.

Limitations of deployment

The share of fusion in the future energy mix depends on several factors



- **Chosen carbon mitigation target**
- **Availability of competing carbon-neutral options for baseload electrical power**
  - Carbon capture and storage
  - Renewables combined with energy storage
  - Nuclear fission
- **Assumed costs of fusion electricity**

Nicolas (2021): intermittent renewables are an attractive solution … if they produce sufficient energy

	Intermittent Renewables (wind + solar)	**Gas + CCS**	**Fission** (e.g. PWR)	**Gen IV Fission** (e.g. Sodium-cooled fast reactor)	**Fusion**	**Fission-Fusion Hybrid**
LCOE	cheap (excluding energy storage)	medium	expensive	expensive	expensive	expensive (but < fusion)
Long-term waste	no nuclear	CO_2 storage	high-level nuclear	high-level nuclear (but spent nuclear fuel < fission)	likely intermediate-level nuclear	high-level nuclear
Nuclear safety risk	no nuclear risk	no nuclear risk	meltdown risk	meltdown risk, but passively-contained	risk of nuclear accident, but not meltdown	risk of nuclear accident, but not meltdown
Weapons proliferation risk (fissile material on site)	no	no	yes	yes	no (but tritium produced)	yes
Resource constraints	rare-earth metals (depends on substitutability)	gas reserves	Uranium-235	Can use Uranium-238	Lithium, but possibly Beryllium	Can use Uranium-238
Scalability	require intermittency solutions at high penetrations	limited by CO_2 storage locations	high	high	high	high
Areal energy density	low	high	high	high	high	high
Load-following	no	fast	rate-limited by thermal inertia	rate-limited by thermal inertia	rate-limited by thermal inertia	rate-limited by thermal inertia
Burn actinide waste?	no	no	no	yes	yes	yes
EROI	~ 50 (wind without storage) ~ 20 (solar without storage)	~ 40	~ 85	$\lesssim 170$	$\lesssim 170$	$\lesssim 170$
Technology readiness level (TRL)	9	8	9	8/9	2/3	3/4

LCOE - levelized cost of energy
EROI - energy returned on invested

Nicolas et al., Energy Policy 2021

Nicolas (2021): fusion may only end up significantly contributing to post-carbon global energy supply

- **Renewables and energy storage cannot solve the decarbonization problem alone**
- **Fusion can help mitigate renewables' intermittency problems, find a niche market such as baseload industrial or district heating**
- **Production of nuclear waste which requires deep geologic disposal is seen as acceptable,**
- **The remaining advantages of fusion over fission are enough to motivate the development of fusion power plants**

$\Rightarrow$ **If none of these things happen, fusion may be relegated to being a post-CCS or post-Uranium technology, to a much smaller market, or simply never become an established technology**

Nicolas (2021): energy policy implications for fusion

- **By the time the government fusion programs demonstrate fusion energy production, the global energy grid will likely have changed very significantly.**
- **A fusion reactor supplying baseload electricity might be obsolete by the time a demonstration device is built.**
- **The fusion community should consider output power modulation when defining research goals.**
  - ➢ Load-following capabilities
- **Fusion research should consider relaxing the low-level waste criterion to accept intermediate-level waste.**
  - ➢ Treating fusion as fission

Material shortages: elements in short supply also include He, Li, Cu, Cr, Mo, No, Nb, Pb and W

- **Helium is vital, non-renewable resource**
  - Superconducting motors, generator, transmission lines, energy storage systems

  ⇒ High gain if He was to be recovered from fusion device

- **Lithium:** competing with other sectors, such as Li car batteries, re-use ^{7}Li after usage in fusion reactors

- **Beryllium:** rare material in bertrandite and beryl
  - Beryllium in helium-cooled pebble bed DEMO approx. 120 t, annual burnup 0.2 t / year ⇒ 100 DEMO-type reactor ≈ 12,000 t / year ⇔ world production at 220 t/year

- **Niobium:** used in steel and superconductors, estimated reserves: 3 Mt

Material shortages: elements in short supply also include He, Li, Cu, Cr, Mo, No, Nb, Pb and W

- **Lead:** DEMO-type reactor approx. 4,000 t, annual burnup 3 t / year, estimated reserves: 1.5 Gt
- **Tungsten:** adequate supplies, estimated reserves 3 Mt

Summary

- **Increase in human development goes hand-in-hand with the increase in energy consumption**

⇒ **Rapidly developing region, both in population and human development, are predicted to consume approx. 5 times more energy by 2100 compared to today**

- **Current (fossil) energy sources could meet energy demands, but exploitation is predicted to lead to unacceptably high CO_2 emission ⇒ global warming and degrading of environment (e.g., smog, acid rain, reduction in life quality)**

- **Fusion of hydrogen isotopes can potentially be a major energy source in the future, offering significant benefits.**

Summary

- **New energy technologies follows an s-curve, exponential-linear-saturation growth phase because of long lifetime. No net energy production at exp. phase.**
- **Fusion may be relegated to being a post-CCS or post-Uranium technology, to a much smaller market, or simply never become an established technology, depending on energy policy, material availability, pricing, etc.**

Backup material

Further, and much more thorough and vetted readings

- **Official government and non-government organizations:**
  - IEA: https://iae.org → https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf
  - https://ec.europa.eu/eurostat/
  - https://stat.fi
  - https://yearbook.enerdata.net
  - ourworldindata.org

Further reading

- **The US National Academies Sciences, Engineering and Medicine 2019:** https://nap.nationalacademies.org/catalog/25331/final-report-of-the-committee-on-a-strategic-plan-for-us-burning-plasma-research

F. Wagner studies on energy mix in Europe (Varenna Energy School 2021)

Varenna energy summer school 2021

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Final wrap-up

Decarbonation is the major global task of this and the next generations

Maybe, such a goal leads to a better global cooperation and understanding

This hope requires a good understanding of all aspects of the transition process

Wind, PV, biomass have to provide the lion`s share

The major political/societal issues concentrate on inclusion of fission and CCS

I think the exclusion of these two options is wrong,
to stop related research is even wronger*

Because of the urgency but also the conflicts with nuclear power
the public is highly sensitive to all aspects of climate and energy transition

As a consequence: the energy field is highjacked by populists also

The only countermeasure: basic understanding of the whole energy field

This is the purpose of this school – and you leave it with a specific responsibility

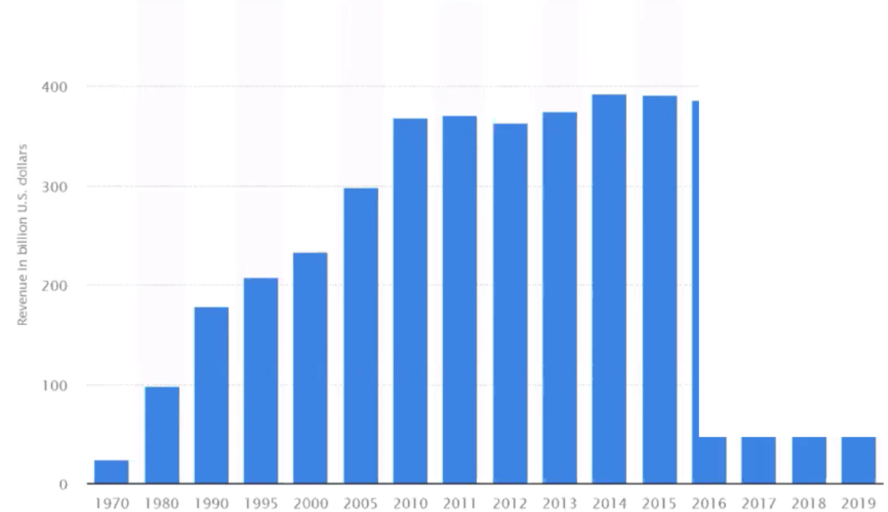
* I am aware that this superlative degree does not exist in English

B. Mumgaard, Commonwealth Fusion Systems: commercialization of fusion

Energy is fundamentally a market

- Power is procured, produced, and sold via market-based mechanisms in most of the globe (exceptions in communist/socialist countries)
  - The markets are tightly regulated by governments
- The same large players sell equipment and operate plants in all the major markets
  - Some of these companies go back 100 years – since power or oil was invented
- Any solution is going to be market-driven and policy-shaped
- It is going to require an industry to deploy new energy technologies

US electricity revenue



Not only is energy a market – it is the largest market in human history!

- The revenue of the publicly traded oil companies are bigger than the GDP of some large nations
- >10M people employed in renewables in the US alone
- Oil and gas industry is ~8% of GDP
- Carbon emissions ~ tonnage of world-wide maritime shipping industry

2/15/2022 Commonwealth Fusion Systems 3

Nicolas (2021): the fusion research community should also explore several additional questions

- **What might the full lifecycle Energy Return On Invested be for modern designs of commercial fusion power plants?**
- **Which materials and elements currently being considered in fusion prototype designs cannot be scaled to hundreds of GW-sized reactors on sustainability or resource availability grounds?**
- **Is the recycling of activated materials from reactor structural materials actually plausible or desirable?**