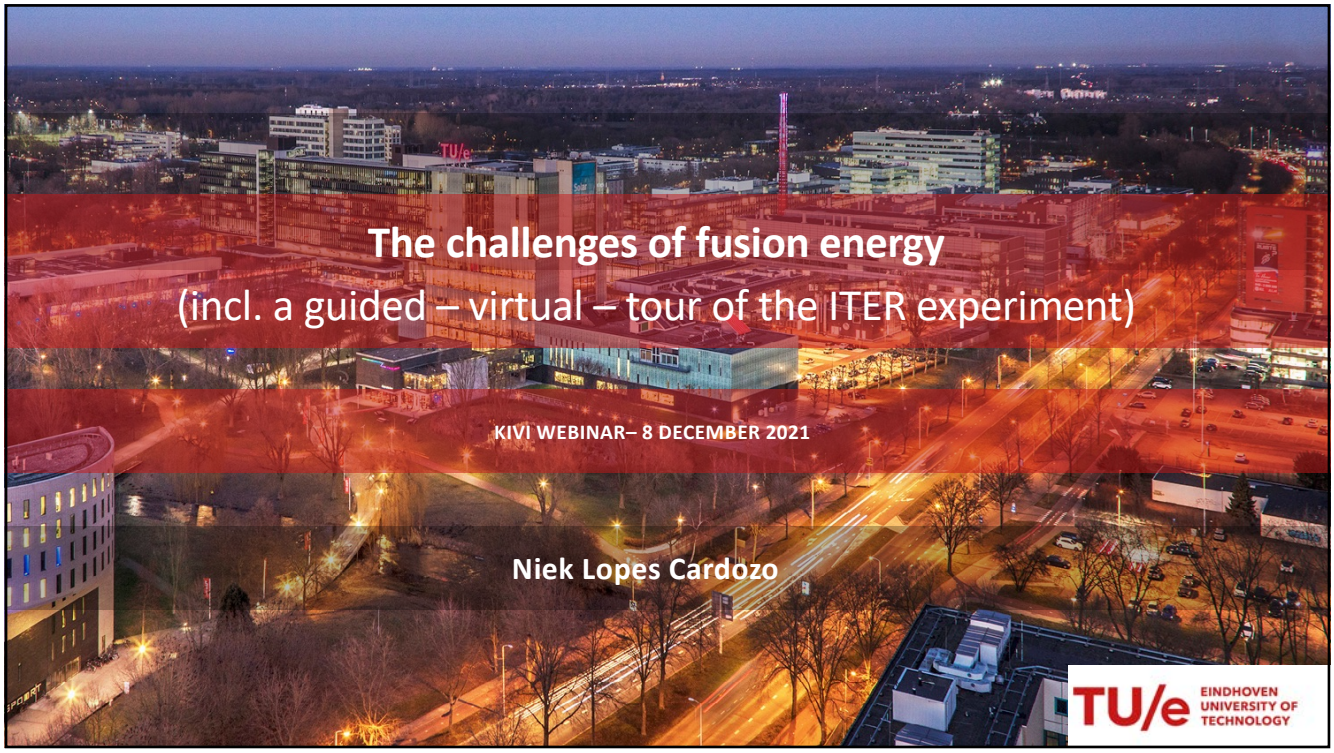

1

Let's not forget what this is about:

the transition to a sustainable world.

"meeting the needs of the present
without compromising the ability of future generations to meet their own needs."
(UN Brundtland committee, 1987)

We cannot foresee the future…

…but we have the moral duty to prepare for it

2

There is much more to the transition than technology….

- Climate change is already affecting the way we live - also in the rich part of the world.
- It is already *upending* the lives of hundreds of millions of people who live elsewhere.

  Floods, draughts, fires, famine, mass migration, political instability …
- The transition will call for cultural and behavioral adaptation as much as it relies on technological solutions

…but we do need technology.

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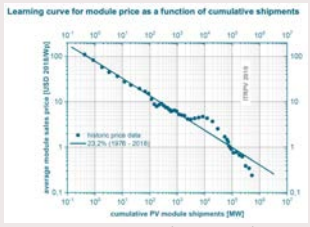
We don't need *just* technology.

We need *new* technology → innovation

- **Incremental** innovation,
  to make known technology better and cheaper.



(ITRPV 2019 – https://itrpv.vdma.org)

- **Radical** innovation,
  to create technology that does not exist yet.

And we need it fast! How fast can we go?

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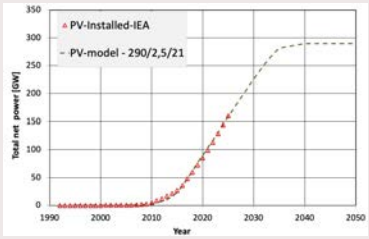
How fast can we go?

Imagine a demonstrator producing 1 MW of green power.
Must scale up by 10^5 to make an impact on global scale.
Doubling every 2 (!) years, that takes >30 years.
And that only brings you to the start of the large-scale deployment (the first bend of the S-curve).

This 2-year doubling is what PV has done for decades (see log plot)

Since a few years it appears to be in the linear part of the S-curve. (see lin. plot)



Data: IEA. (note this includes a forecast to 2025)
I applied an averaged capacity factor to translate 'installed power' into 'net power' based on the 'generated energy' data.

But this linear rate is

a. about a factor 10 too slow to achieve the 2050 goals; and

b. will saturate after ~one lifetime of the installed panels (dashed line).

Formative phase takes decades…

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How fast can we go?

- Formative phase: New technology needs decades to build up the industrial capacity needed for large scale deployment.
- So, 'fast' implies: scaling up what's already big.
- How can we still have the benefits of innovation in this rapid expansion process?
- How do we avoid technology lock-in?

and how does nuclear fusion enter this story?

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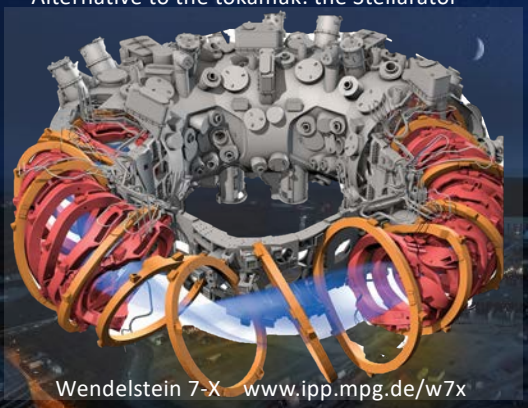
The mainstream fusion Roadmap: ITER

ITER is a 'tokamak'
(most common type of fusion reactor)

Alternative to the tokamak: the Stellarator



Wendelstein 7-X www.ipp.mpg.de/w7x

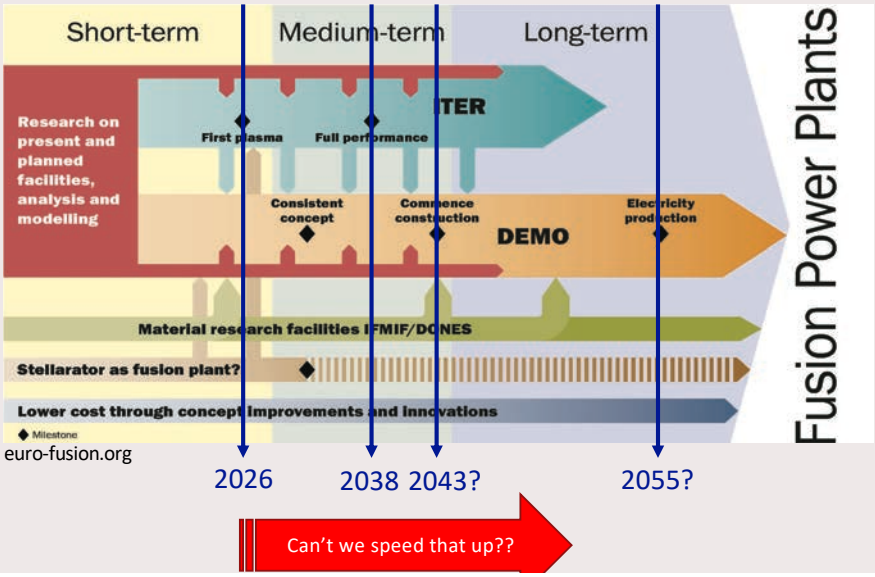
Magnets to keep the plasma in place

The fuel: plasma @ 150 million C

graphics: ITER.org

7

The mainstream fusion Roadmap: no electricity in 2050



euro-fusion.org

Can't we speed that up??

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Fusion: the rive gauche …. Exciting times!

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Privately funded fusion R&D is booming

FUSION INDUSTRY ASSOCIATION

Commonwealth Fusion Systems, tae TECHNOLOGIES, generalfusion, AVALANCHE, ALBOT, HYPERJET FUSION CORP, HELION, tokamak energy, TYPE ONE ENERGY, PrincetonSATELLITE SYSTEMS, INNOVEN Energy, HelicityFusion, nearstar FUSION, fuse, HORNE TECHNOLOGIES, FOCUSED ENERGY, HB11 ENERGY, ZAP ENERGY, RENAISSANCE FUSION, NK, MIFTI, CTFusion As Brilliant as the Sun, LPP FUSION, first light

Source: https://www.fusionindustryassociation.org/

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The supply and manufacturing industry is shaping up, too

Source: https://www.fusionindustryassociation.org/

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Privately funded fusion R&D is booming

- All claim 'faster, smarter, sooner' (and cheaper)
- A great variety of different concepts

  from 'conventional +' to totally out of the box

The Big Read Energy sector + Add to myFT

Nuclear fusion: why the race to harness the power of the sun just sped up

Advances in technology and funding have sparked optimism in an area that has promised much but delivered little in six decades

Tom Wilson in Oxford and Ian Bott in London NOVEMBER 24 2021

(Financial Times 24 Nov 2021)

- Attract significant venture capital (billions for the largest, millions for the smaller ones)
- Some have outstanding teams. They are serious enterprises.
- Chances of success of each individual enterprise … hmm, varies (in my estimation)
- Together: rich bath of ideas and innovations. (Also transferable technology)
- Bring enormous drive to the table!

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But ... wasn't fusion supposed to be hard to achieve?

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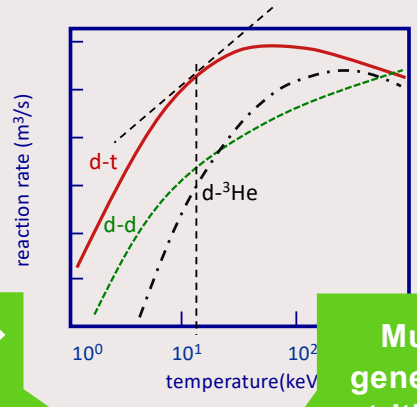
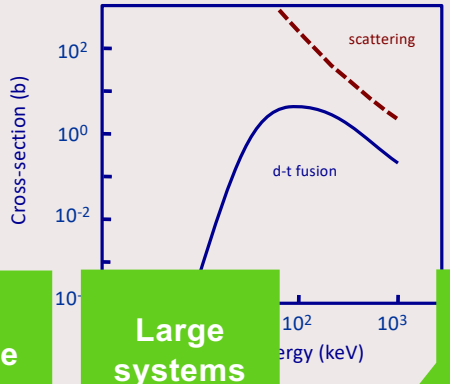
Why is fusion difficult?

Reaction needs high T



Scattering is more likely than fusion



Neutrons →
- materials
- activation

Must generate tritium

Large systems

Thermal wall load

→ Burn d-t at 15 keV
(and forget about other fuel)

→ need confinement

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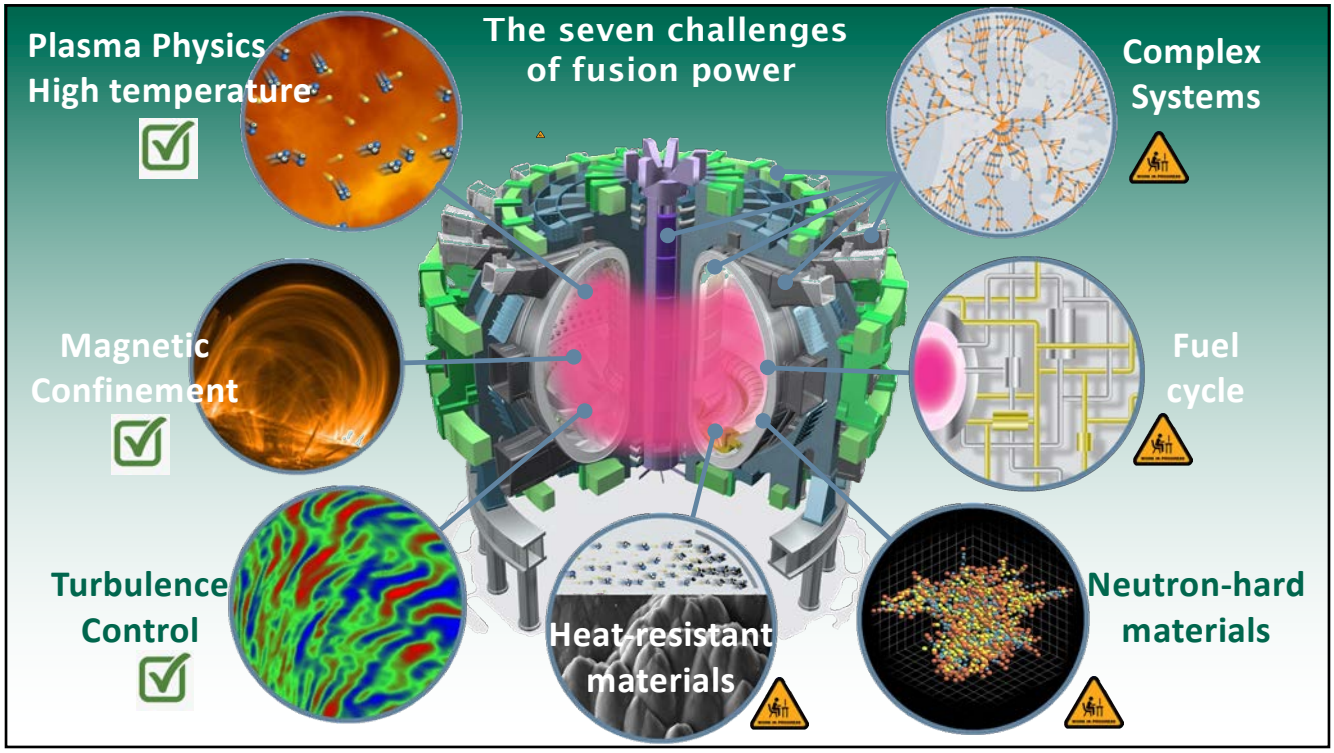

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How can start-ups claim to go so much faster?

CFS's path to commercial fusion energy:

- 2018: Company founded based on decades of MIT fusion research
- 2020: Published a series of peer reviewed publications in the Journal of Plasma Physics that verifies SPARC will achieve net energy from fusion
- 2021: Started construction on campus that will host the SPARC building, a manufacturing facility, and company headquarters
- 2021: In collaboration with MIT, built and successfully demonstrated groundbreaking high temperature superconducting magnets, the strongest of their kind and the key technology to unlock commercial fusion energy
- 2025: SPARC achieves commercially relevant net energy from fusion
- Early 2030s: First fusion power plant, called ARC, is completed

SPARC is 'ITER-like' in performance

ARC is 'DEMO-like' in performance

"The world is ready to make big investments in commercial fusion as a key part of the global energy transition. This diverse group of investors includes a spectrum of capital from energy and technology companies to venture capitalists, hedge funds, and university endowments that believe in fusion as a large-scale solution to decarbonize the planet," said CFS CEO Bob Mumgaard.

The EUROfusion roadmap:

- 2006 ITER agreement signed
- 2026 ITER first plasma
- 2038 ITER full performance (dt)
- 2043 Go-ahead DEMO
- 2055 Start commissioning DEMO
- 2060 DEMO electricity to grid
- 2070 Gen1 fusion construction completed

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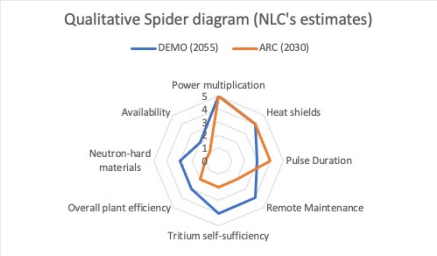
How can start-ups claim to go so much faster?

1. They do not take on all issues at the same time (e.g. worry about neutron-hard materials later)



→ Accept that if your goal is to build 10000 reactors, then the first batch(es) are irrelevant for power generation. No need to make them efficient or long-lasting or clean

→ Accept that the exponential phase is only there to figure out the best design/technology and build the industrial capacity for rapid deployment
→ (strange as it may sound) build discardable reactors.

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How can start-ups claim to go so much faster?

1. They do not take on all issues at the same time (e.g. worry about neutron-hard materials later)
2. They minimize complexity of design
3. They opt for the high-risk-high-gain approach

→ Venture capitalists are willing to take that risk, governments are not

Innovations

Use all the knowledge and technology from mainstream
Use innovations from outside (e.g. HTS tape, 3D-printing, AI, control technology)
Own innovations (e.g. design and fabrication of 20 Tesla HTS coil)
The one drives the other: 70% of all REBCO tape ever produced is used in the CFS magnet

Together they represent evolutionary, parallel development.

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Back to the dream…

Bob Mumgaard (Commonwealth Fusion Systems):
"Imagine 2050. We've got *ten thousand* fusion power plants providing 20% of the world's energy consumption"

https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908

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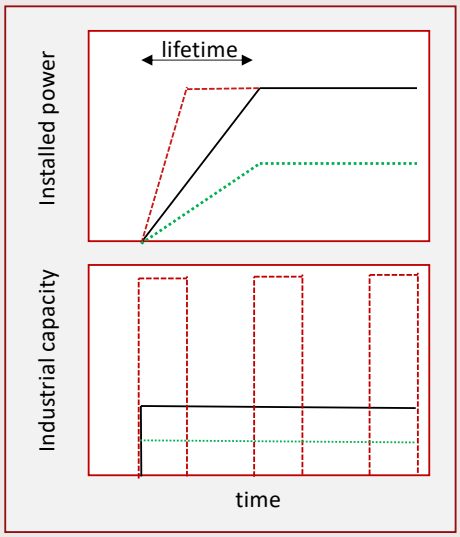
Ten thousand fusion plants in 2050, what does that take?

- 500 per year @ >2 Billion each……
  Oops! That is a seriously big business
  (50 x fission industry today; 5 x Apple; 1-2 % of global GDP)

➢ That takes time to grow

- If the plants have a life time of 50 years:
  - only 200/y industrial capacity is eventually needed
  - In 2050 there will be a gap of 30 years with no business.
  - (or continue to grow at reduced speed …could be ok)



500 plants per year…. that's a hard sell.
But we do need 10000 *something* plants, for which the same holds.

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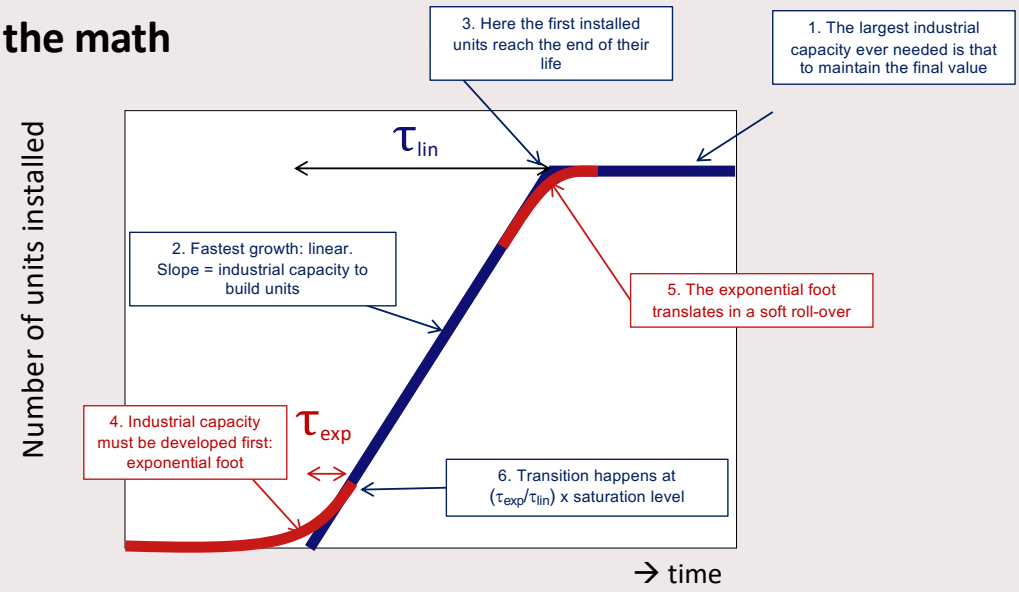
Let's do the math



(This is the fastest possible development in which the industrial capacity is continuous and monotonic)

Work with G.J. Kramer (UU) and G. Lange (EUROfusion)

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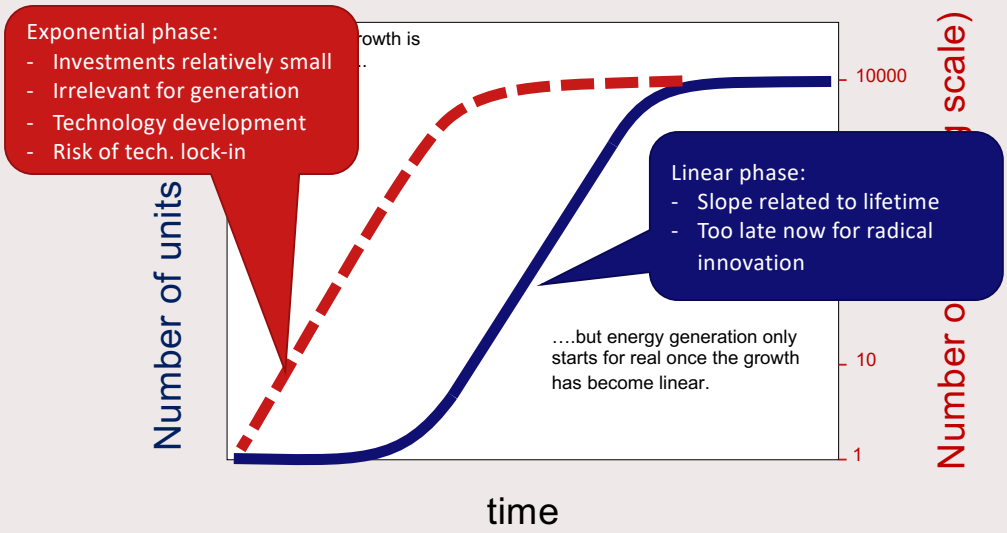
Let's do the math



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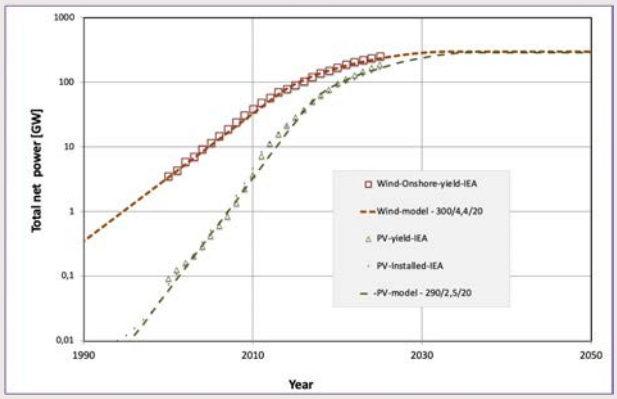
Aren't renewables subject to the same logic?



Fits of model (exponential growth + linear growth until saturation after 1 lifetime (= τ_{lin})) to IEA data. Model parameters: $P_{saturation}/\tau_{exp}/\ \tau_{lin}$

This model is not a prediction of the future. It just states at which level the present production rate will saturate.

That is a no-brainer. However: it shows that the present growth rate of RET is about 10x too slow to realise the transition.

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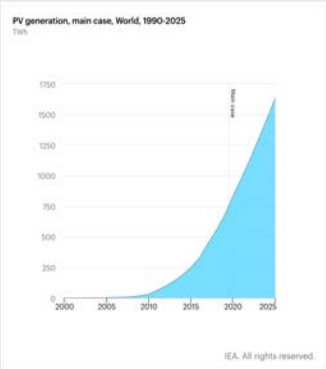
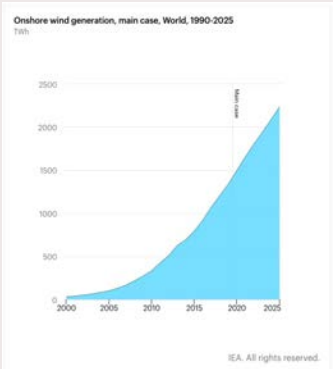
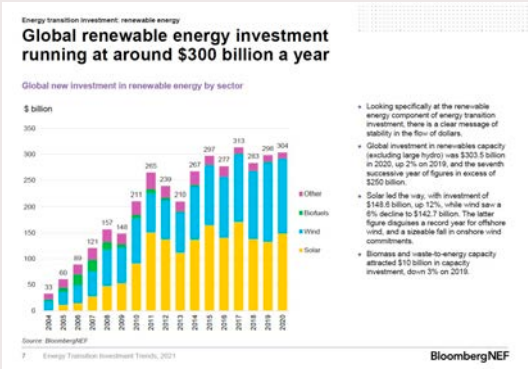
PV and Wind have abandoned exponential growth….







...which ties in with the fact that RET investments have stalled @ 300 billion/year since ~2011

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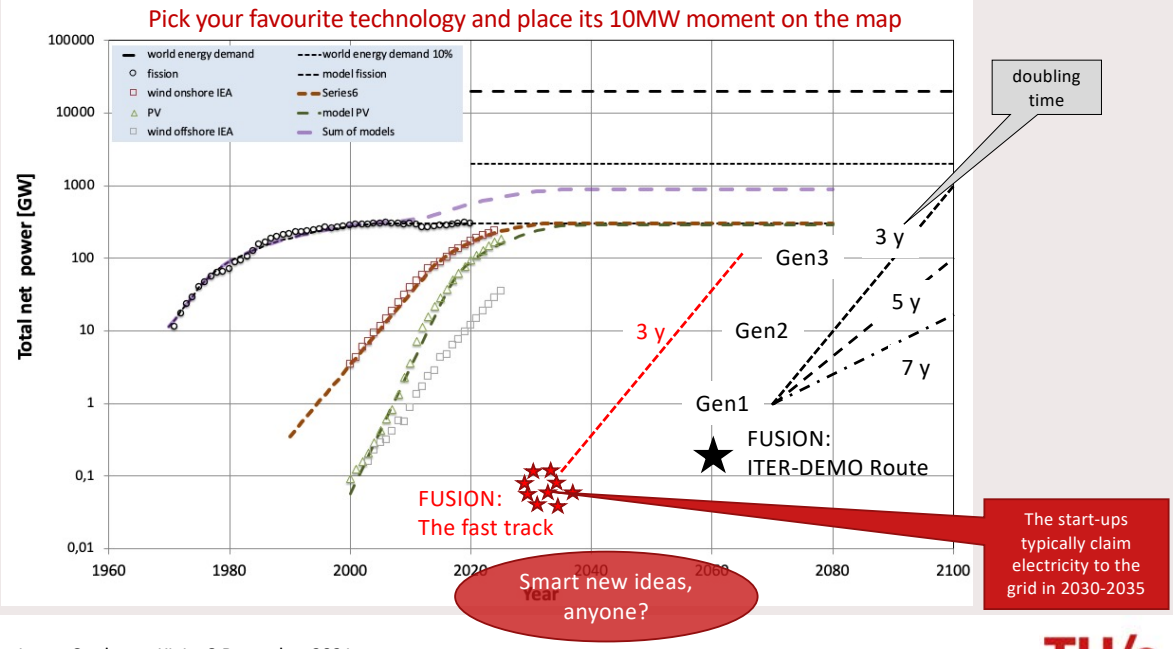
The one plot that tells it all



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Conclusion: Invest in parallel innovation in early phase

Fast transition → must scale up what's already big.

Linear growth:

transition asks for annual investment of trillions (few% of global GDP) ~ independent of technology
limited by lifetime of product (so no, the energy transition will not come as fast as the smartphone did.)

Exponential pre-growth (formative phase):

needed to build industrial capacity.
negligible contribution to CO_2 reduction
how to avoid technology lock-in?

Fusion is a case study

long build time – big jumps between generations – wide valley of death
mainstream roadmap: risk-averse, 1-dimensional, guarantees lock-in, no electricity before 2050
private companies: high-risk, parallel development of ideas, innovative.

Can't foretell the future → must create an *option space* for next generations

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