Why we have solar panels but not yet fusion power.

Niek Lopes Cardozo

Guido Lange

Gert-Jan Kramer (Shell Global Solutions).

Technische Universiteit Eindhoven University of Technology

Where innovation starts

Grand Challenges

- Introduction
- Make solar energy economical
- Provide energy from fusion
- Develop carbon sequestration methods
- Manage the nitrogen cycle
- Provide access to clean water
- Restore and improve urban infrastructure
- Advance health informatics
- Engineer better medicines
- Reverse-engineer the brain
- Prevent nuclear terror
- Secure cyberspace
- Enhance virtual reality
- Advance personalized learning
- Engineer the tools of scientific discovery

Introduction
Make solar energy economical
Provide energy from fusion
Develop carbon sequestration methods

Grand Challenges

The Grand Challenges for Engineering as determined by a committee of the National Academy of Engineering.

Email This
Print This

The century ahead poses challenges as formidable as any from millennia past.

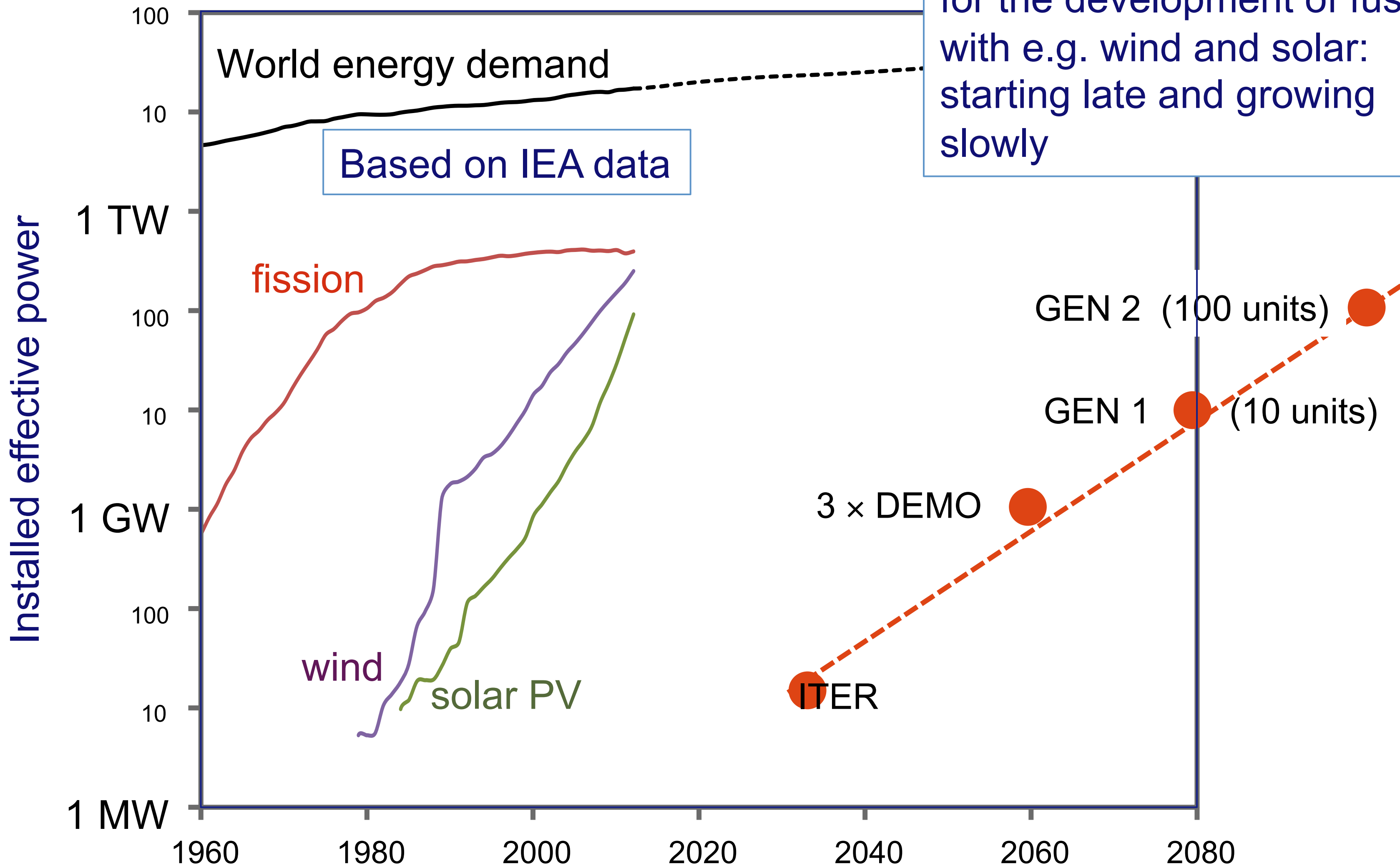
Watch the video (6:27)

Here are the Grand Challenges for engineering as determined by a committee of the National Academy of Engineering:

- Make solar energy economical
- Provide energy from fusion
- Develop carbon sequestration methods
- Manage the nitrogen cycle

When will we have fusion power?

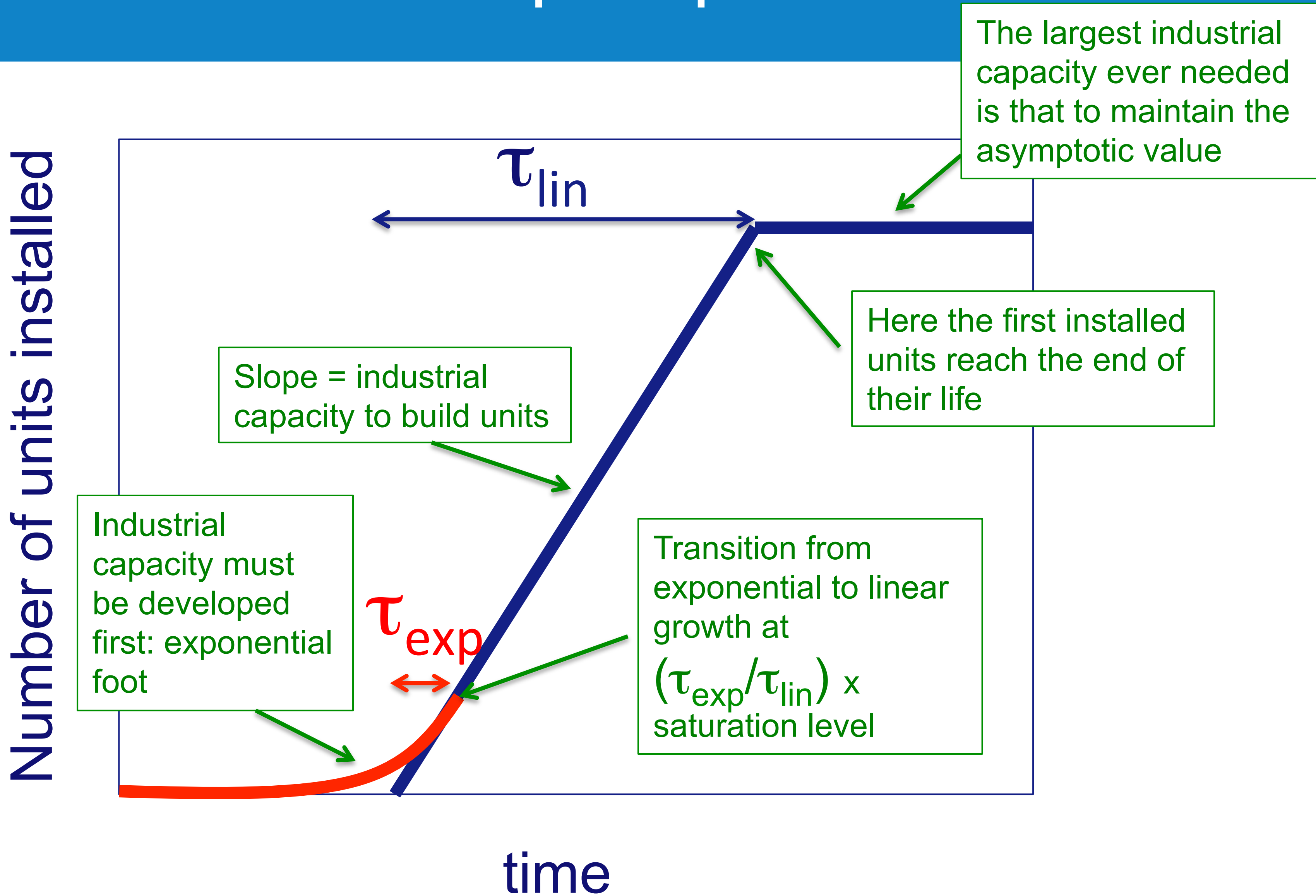
Compare a 'realistic' scenario for the development of fusion with e.g. wind and solar: starting late and growing slowly



Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

TU/e Technische Universiteit Eindhoven University of Technology

What is the fastest development path?



Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

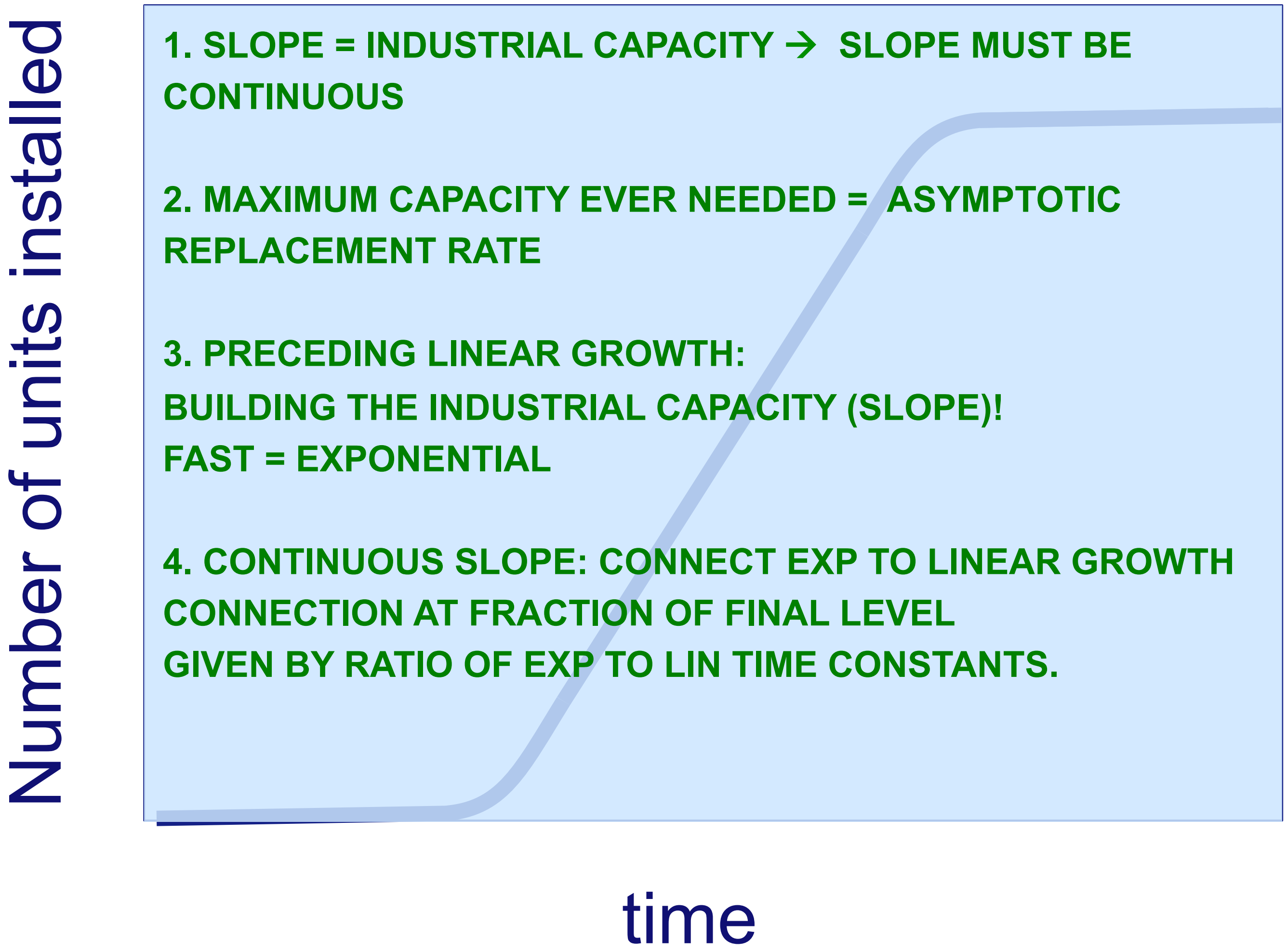
What is the fastest development path - summary

1. SLOPE = INDUSTRIAL CAPACITY → SLOPE MUST BE CONTINUOUS

2. MAXIMUM CAPACITY EVER NEEDED = ASYMPTOTIC REPLACEMENT RATE

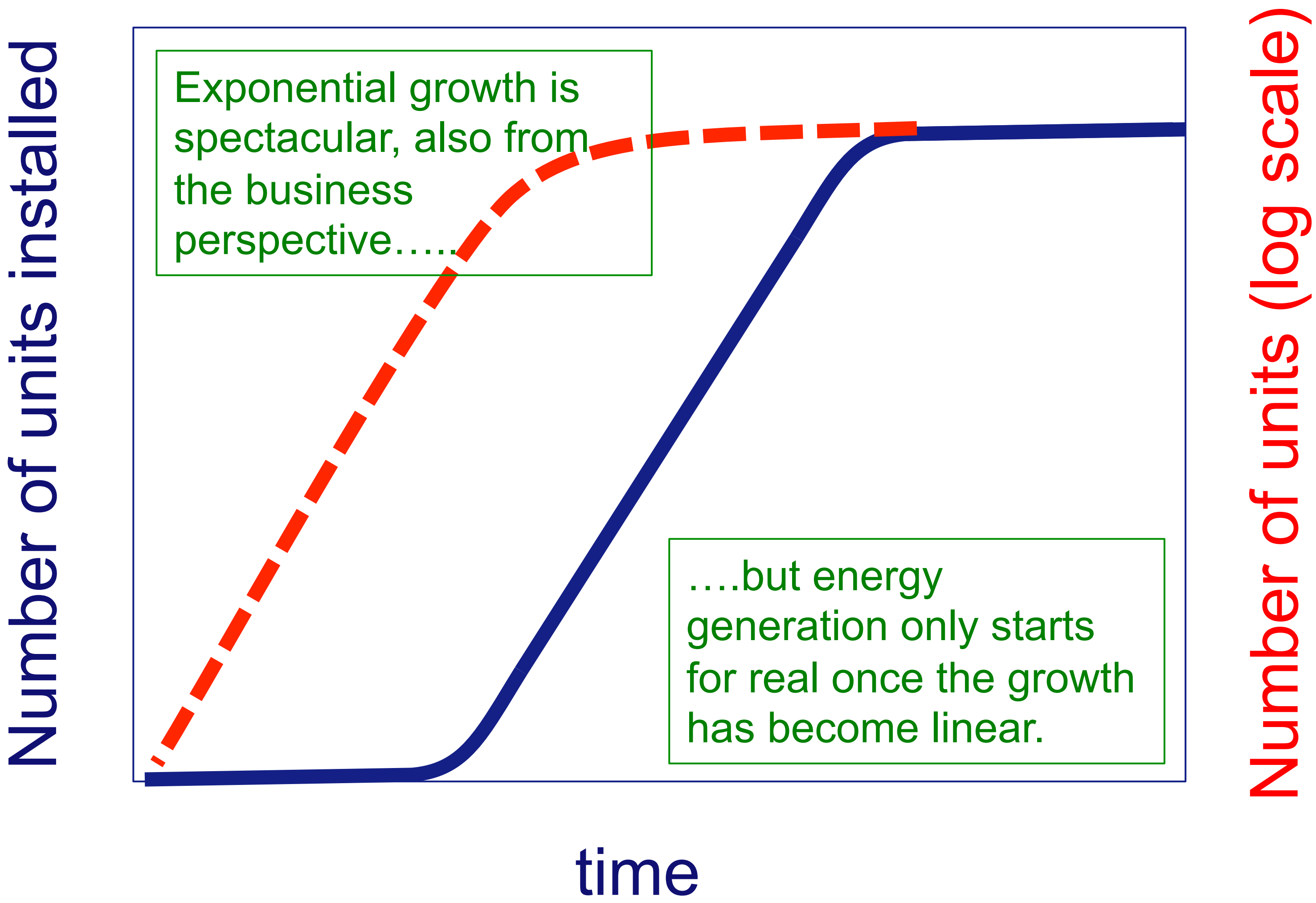
3. PRECEDING LINEAR GROWTH:
BUILDING THE INDUSTRIAL CAPACITY (SLOPE)!
FAST = EXPONENTIAL

4. CONTINUOUS SLOPE: CONNECT EXP TO LINEAR GROWTH
CONNECTION AT FRACTION OF FINAL LEVEL
GIVEN BY RATIO OF EXP TO LIN TIME CONSTANTS.



Technische Universiteit Eindhoven University of Technology

What is the fastest development path?



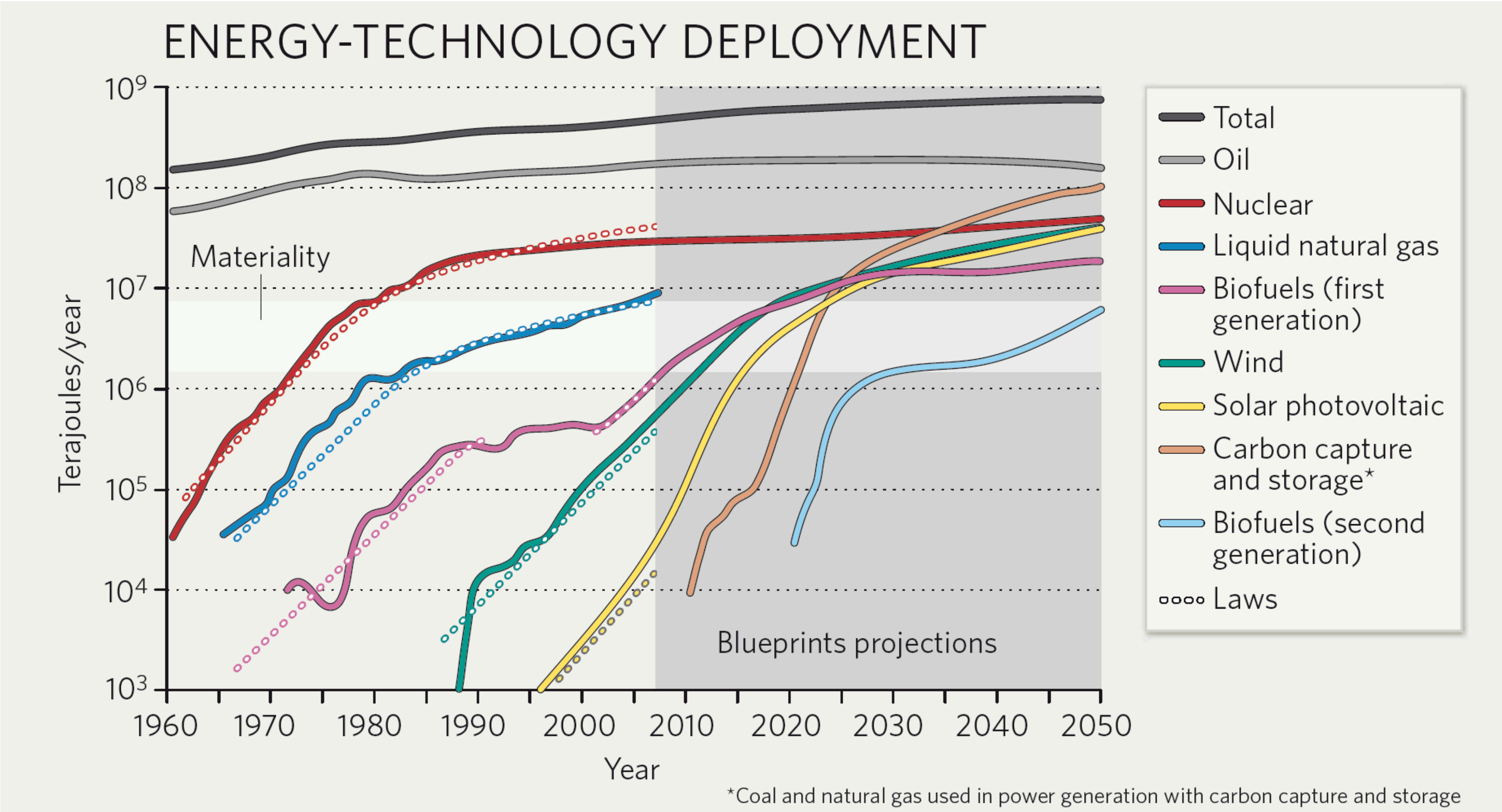
Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

(Some caveats: linear growth can go faster if…)

- If ‘final’ level still shows moderate growth: total capacity needed = replacement + growth
- If industrial infrastructure is cheap or short-lived
- If industrial capacity needed to build energy infrastructure can be redeployed once it is no longer required

Historical data (IEA): G-J Kramer and M Haigh

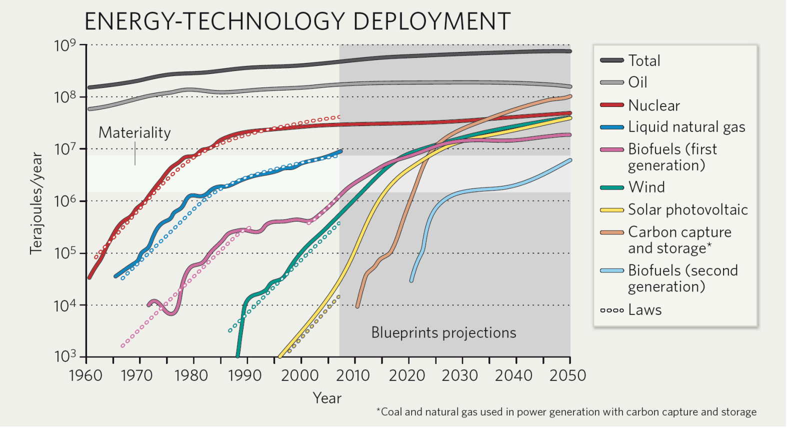
No quick switch to low carbon energy, Nature, Dec 2009



Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Starting point: G-J Kramer and M Haigh,
No quick switch to low carbon energy, Nature, Dec 2009

Upshot of the paper: ALL new sources show

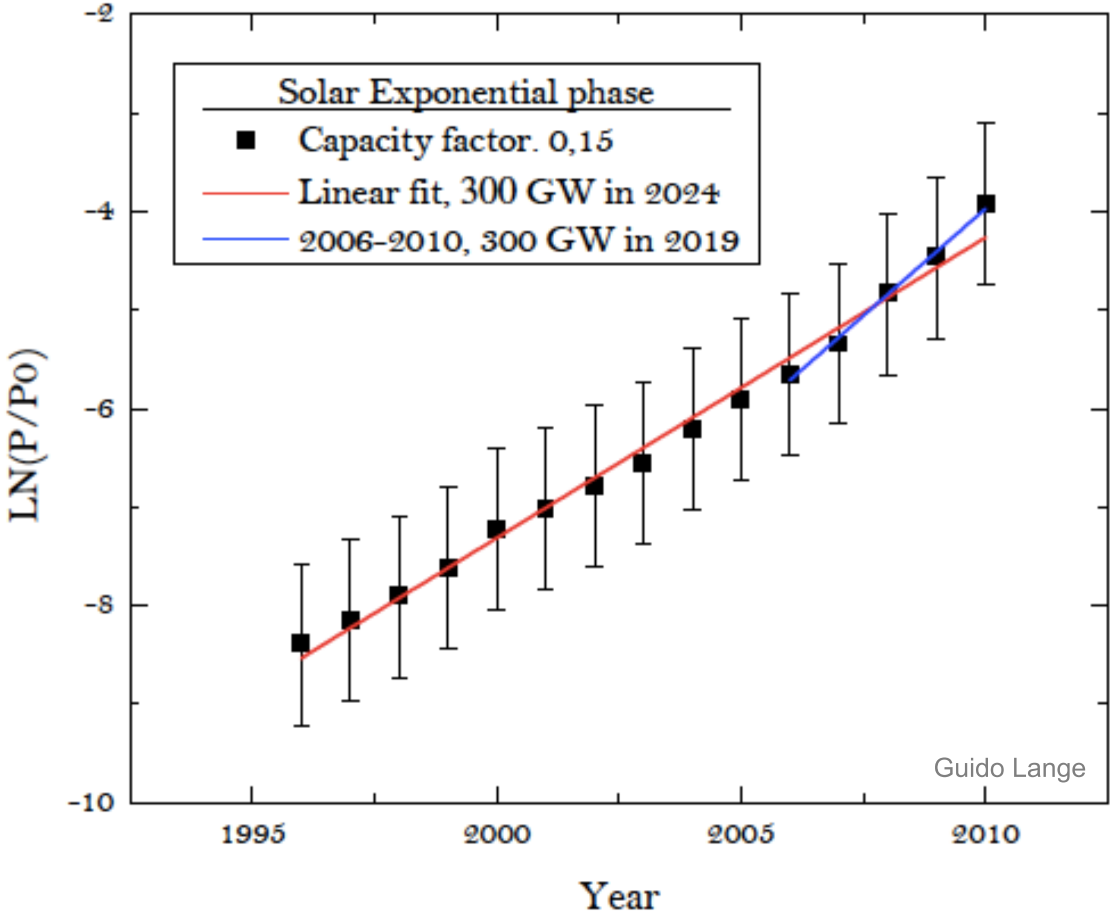


- **exponential** growth up to ‘materiality’
  - Materiality: 1-10% of final installed power
  - Doubling time during exponential growth typically 2-4 year
  - Taking 3-4 decades

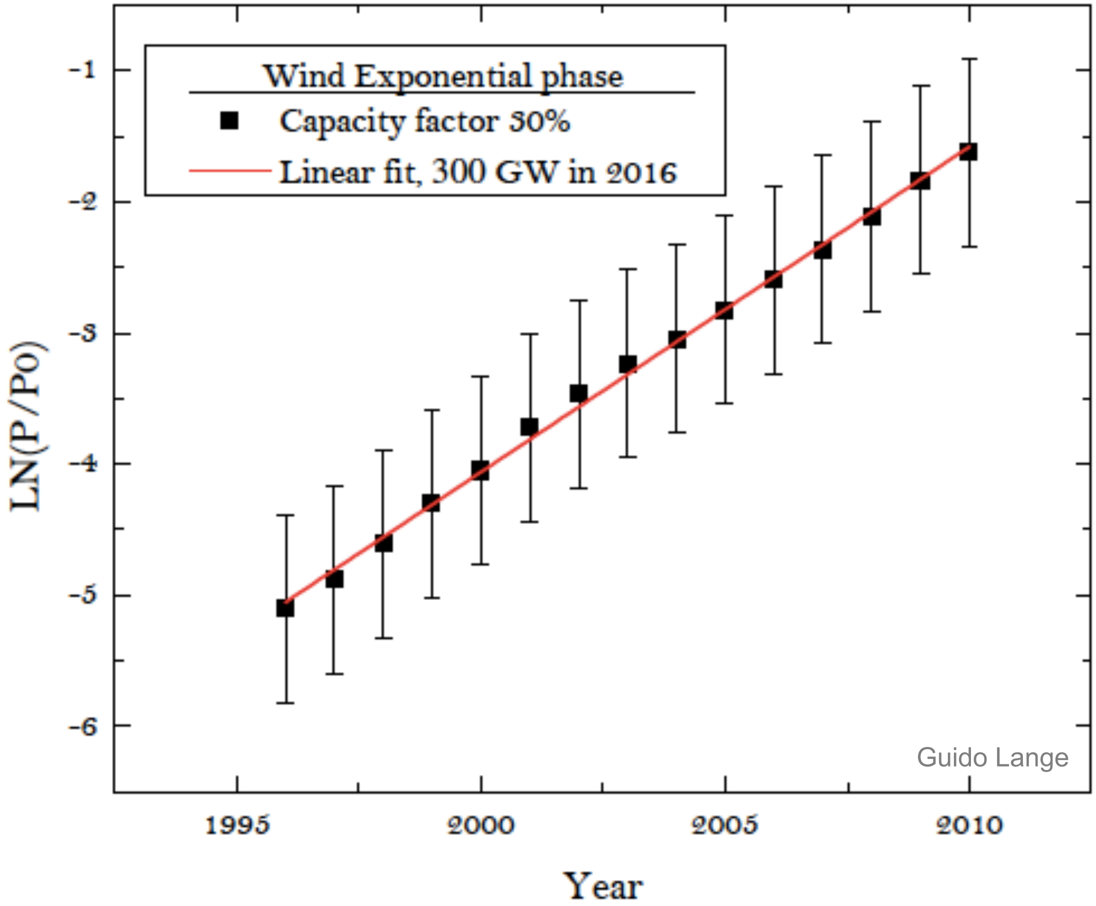
- Followed by **linear** growth: typically a few decades, too.

Therefore: ‘no quick switch to low carbon energy’

Historic data: photovoltaic (PV).



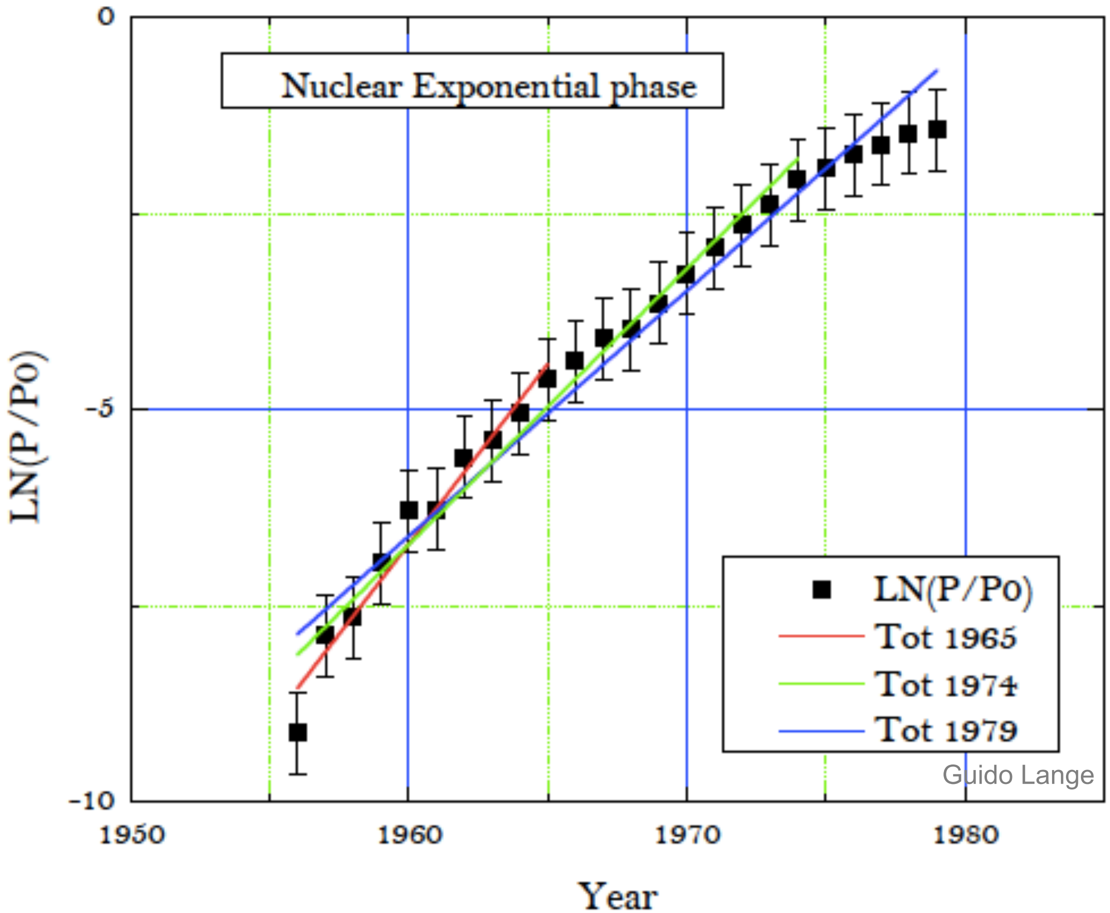
Historic data: Wind.



Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Technische Universiteit Eindhoven University of Technology

Historic data: Fission.



Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Key parameters for various technologies

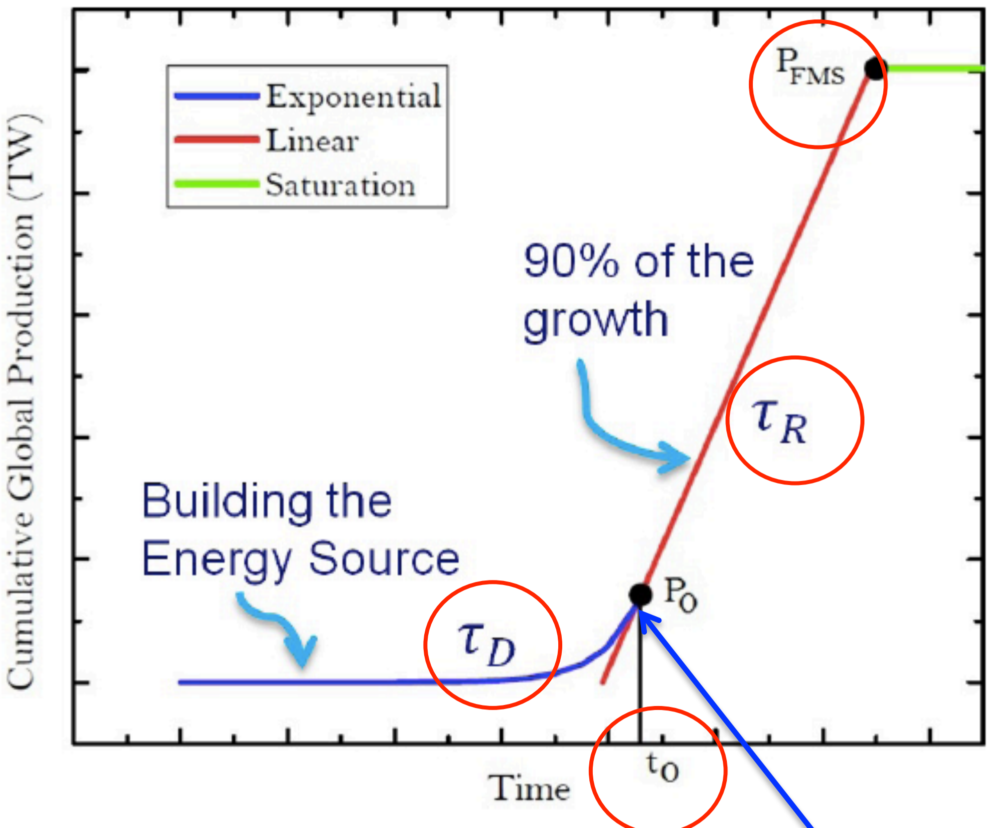
Technology	Doubling time	Life time
Fission	2.2	40
PV	2.3	30
CSP	3	30
Wind	4	30
Ethanol	4	40
Coal-CCS		35

Guido Lange

Simple model: universal curves taking fixed

- Doubling time (e.g. 3 y) and
- Life time (40y)

Again: the universal growth curve, determined by 4 parameters only



Final Market Share:
P_{FMS}: typically 10-20% of World Energy Demand

Linear growth: replacement time
τ_R : typically 30 -50 years

Exponential growth: doubling time
τ_D : typically 2-4 years

Plus the trivial parameter to fix the time frame

Slope = production capacity → slope is continuous

Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

TU/e Technische Universiteit Eindhoven University of Technology

Exponential growth phase: energy production irrelevant

- The energy production in the exponential phase is irrelevant

  Obvious: since the exponential growth stops at typically 1% of the final capacity, i.e typically 0.1 % of world energy demand.

- If the *doubling time* is shorter than the *energy payback time* the net energy production is even *negative* during the entire exponential growth phase.

  This is e.g. the case for photovoltaic.

- All of this is not a criticism.

  It just states that a system has to go through a growth phase before it starts to produce.

  This phase builds the industrial capacity needed to build and maintain the future park.

  Energy production during this phase is irrelevant.

→ Exponential growth phase = building up industrial capacity

→ Exponential growth phase: investment in a future energy source.

Exponential growth phase: how does fusion fit in? It does not produce any power yet!

- If energy production in exponential growth phase is irrelevant, we need to define a ‘hypothetical’ power to characterize the state of development of an energy source.

- For Fusion the net power output is not a relevant number to characterize the state of development.
  - A good measure is: fusion power level.
  - But in order to produce comparable numbers to other energy source, we must include
    - (hypothetical) efficiency of electricity generation, and
    - (hypothetical) availability

- Plot the Fusion Road Map in the picture

Assumptions on fusion output power (world roadmap)

- ITER: P_{fusion} = 500 MW.
  hypothetical $P_{electric}$=150 MW. Availability = 10%.
  → hypothetical power: 15 MW by 2026

- DEMO: 3 plants, 1.0 GW_e each, availability 30%
  → hypothetical power: 1.0 GW by mid 40ties

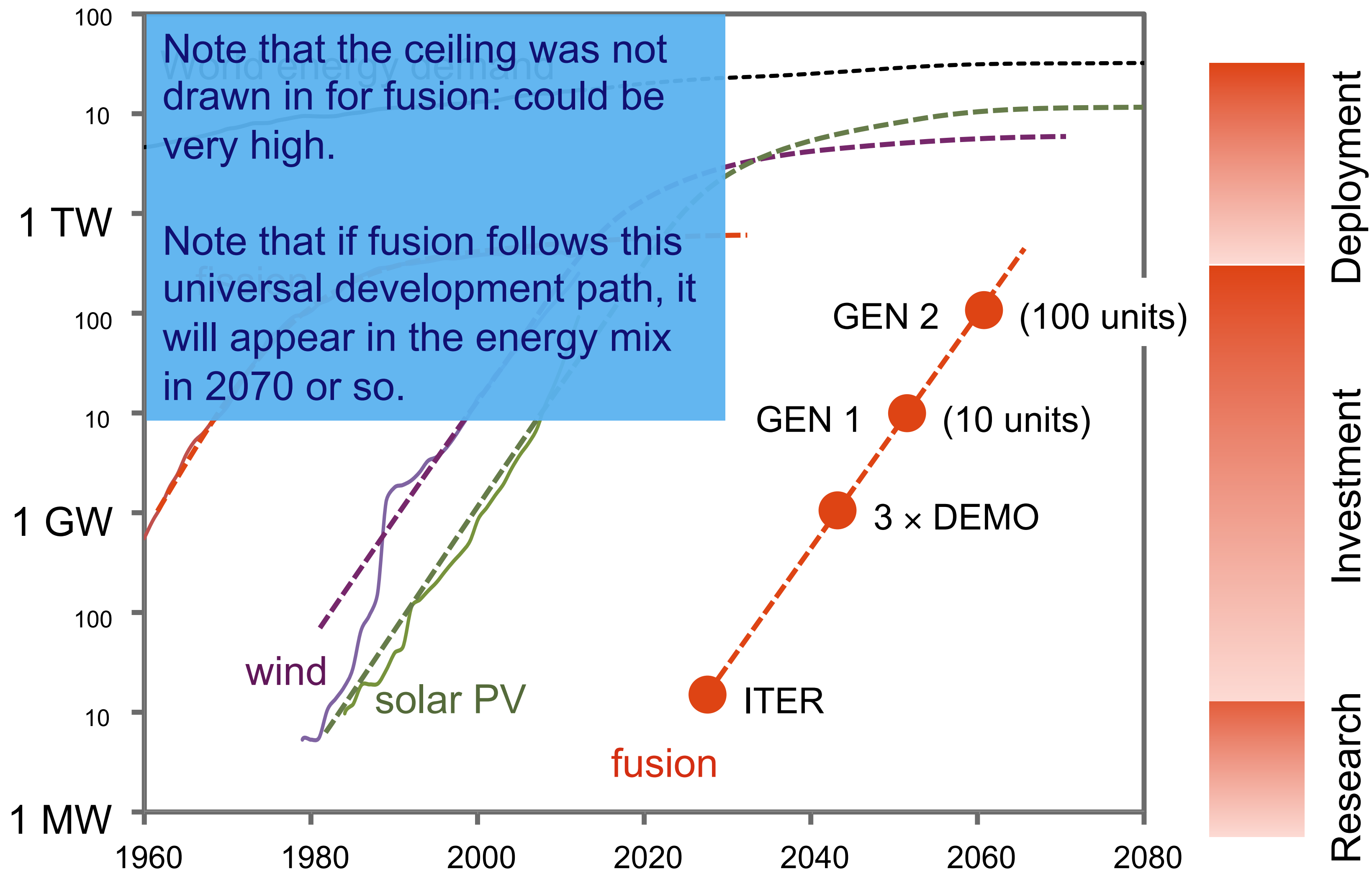
- Gen1: 10 plants, 1.7 GW_e each, availability 50%
  → hypothetical power: 8.5 GW_e by mid 50ties

From there: doubling in 3 years = tenfold growth in 10 years.

- Gen2: 100 plants, 1.7 GW_e each, availability 60%
  → hypothetical power: 100 GW_e by mid 60ties

Technische Universiteit Eindhoven University of Technology

Universal growth model – and how does fusion look?



Note that the ceiling was not drawn in for fusion: could be very high.

Note that if fusion follows this universal development path, it will appear in the energy mix in 2070 or so.

Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Fusion: Taking forever?

My conclusion:

- Fusion Road Map: could follow universal development curve
- Then: Fusion enters energy mix around 2070. Not ‘far too’ late.
- This roadmap, going to 10 Gen1 plants in the mid 50ties, is extremely challenging, BUT
- Fusion: if we do not stick to the roadmap, fusion becomes irrelevant as energy option.
- Realization of this roadmap implicitly presumes a strong increase in the investment rate.

So: how about ‘incredibly expensive’?

Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Exponent

- Having …) during the exp … ved.
- During … tment (‘overni …
- This is … ge 3-6 $/W_{insta}$ … uring develo … luded, i.e. inte …
- Folding … quired to reali …
- An indi … 257 Bill …

Table 2. Comparison of Updated Plant Costs to *AEO2010* Plant Costs

Table II

	Overnight Capital Cost ($/kW)			Nominal Capacity KWs[1]	
	AEO 2011	AEO 2010	% Change	AEO 2011	AEO 2010
Coal					
Advanced PC w/o CCS	$2,844	$2,271	25%	1,300,000	600,000
IGCC w/o CCS	$3,221	$2,624	23%	1,200,000	550,000
IGCC CCS	$5,348	$3,857	39%	600,000	380,000
Natural Gas					
Conventional NGCC	$978	$1,005	-3%	540,000	250,000
Advanced NGCC	$1,003	$989	1%	400,000	400,000
Advanced NGCC with CCS	$2,060	$1,973	4%	340,000	400,000
Conventional CT	$974	$700	39%	85,000	160,000
Advanced CT	$665	$662	0%	210,000	230,000
Fuel Cells	$6,835	$5,595	22%	10,000	10,000
Nuclear					
Nuclear	$5,339	$3,902	37%	2,236,000	1,350,000
Renewables					
Biomass	$3,860	$3,931	-2%	50,000	80,000
Geothermal	$4,141	$1,786	132%	50,000	50,000
MSW - Landfill Gas	$8,232	$2,655	210%	50,000	30,000
Conventional Hydropower	$3,078	$2,340	53%	500,000	500,000
Wind	$2,438	$2,007	21%	100,000	50,000
Wind Offshore	$5,975	$4,021	49%	400,000	100,000
Solar Thermal	$4,692	$5,242	-10%	100,000	100,000
Photovoltaic	$4,755	$6,303	-25%	150,000	5,000

[1] Higher plant capacity reflects the assumption that plants would install multiple units per site and that savings could be gained by eliminating redundancies and combining services.

Overnight cost for various technologies

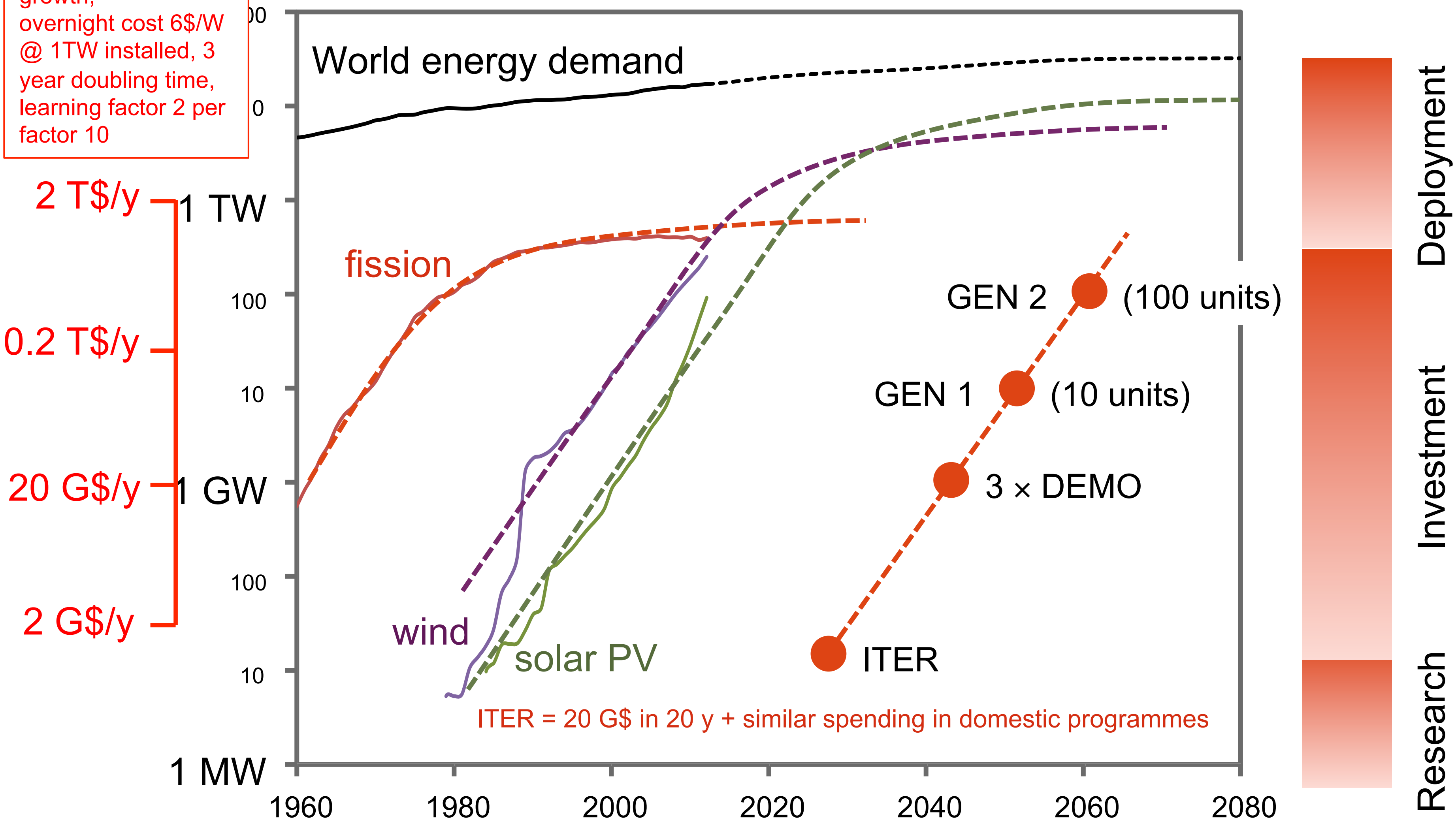
Technology	Overnight cost ($/W)	Capacity factor	Overnight cost effective
Fission	5-7	0.9	5-7
PV	3 - 5 (and falling)	0.1-0.2	25-50
Wind	2.5	0.2	12.5
Wind off-shore	6	0.4	15
Coal-CCS	5	0.7?	7

Learning effect: depends on technology.
Usually factor 2 price drop for every factor 10 installed power

Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Universal growth model – price tags (overnight cost)

Spending rate during exponential growth, overnight cost 6$/W @ 1TW installed, 3 year doubling time, learning factor 2 per factor 10



Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

Technische Universiteit Eindhoven University of Technology

Exponential growth phase: serious money involved!

During exponential growth, at 1 to 100 GW_e total installed power, budget required: tens to hundreds of Billion Euro/year!

Over entire exponential growth: 1000 – 2000 Billion Euro invested.

(cp Fusion: 100 Gen2 plants @ 10 - 20 Billion each)

As no significant energy is produced yet:

This is tax payers money, invested in a future energy source.

No source has been developed without government support in one form or another.

This investment anticipates the payback by 30 years or more.

How is fusion comparable to other sources?

- Roadmap – if realized – could follow the same universal curve

- Spending rate, total investment typical for present development phase.
  (but does fusion have scope for learning effect?)

- 30 years behind Wind and PV, but not 'too' late.
  (Note: other new sources, and storage, are still in the lab phase, still have to start their exponential growth)

Lopes Cardozo, Lange, Kramer; Why we have solar cells but not yet nuclear fusion

How is fusion different?

- Capital investment per unit is big.
  - This is a real problem, especially during exponential growth. *Valley of death* between Gen1 and Gen2?
  - Possibly balanced by promise of ‘clean, safe, for ever, for all’ and potentially large contribution to world energy production. But hampered by uncertainty (see below)
  - Need for a smart funding scheme. Compare PV ‘crowd funding’!

- Technology readiness level/uncertainty
  - Still early in the industrial development
  - ITER must make a big step here
  - But from ITER to DEMO is another big step
  - And from DEMO to 70% availability is yet another big step.
  - Intrinsic complexity? Can fusion be simpler, cheaper, more reliable?

How is fusion different? – 2 -

- Fusion does not make energy yet.

  During exponential growth this should actually not matter, as long as there is the guarantee that there will be energy production when 'materiality' is reached. But

  a. it helps a lot if your demonstration model does produce power, and
  b. the public/investors/politicians may not have this ultimate insight.

  → Hard sell.

- Fusion does not appeal to the individual energy user.
  - ✧ 'Crowd funding' schemes (such as German feed-in tariff) or citizens initiatives not likely to work.
  - ✧ For individual fusion investor: long economic pay-back time.

- Finally: is fusion (perceived to be) needed?

Cost of a new energy source

- The total investment needed for a new energy source, until the start of the linear growth (deployment), *ie before energy production starts*, is simply given by the then installed power times the overnight cost, with a correction for the learning effect.
- Total investment needed *before* production: 1-2 trillion Euro.
- Total investment for 10% of world energy: tens of trillion Euro.

(Compare: energy market EU: one trillion Euro/year.)

→ To R&D a new energy source 1 billion Euro/year is a lot.
Yet, that is < 0.1% of the cost to even bring it to 'materiality'.
→ Develop every option (there are only a few anyway)

The question is: Is fusion (perceived as) a fall-back option or a necessity?

Technische Universiteit Eindhoven University of Technology

Conclusions: expensive and taking forever?

- Fusion is NOT much more expensive than other energy options, the budget is typical for the phase of the development.
- Present Fusion Road Maps start out compatible with the development lines of other sources.
- But we must stick to those dates: Gen1 fusion in early 2050 and then doubling every 3 years. If not fusion is later and slower than others. Then it really is: '*expensive and taking forever'.* Not credible as an energy option.
- To realize this roadmap, the budget must grow exponentially, too. Don't pretend we can do it with steady budget.
- A typical budget in the ITER Era, i.e. from 2030 or so, would be 10 G$/year
- By that time the program should be technology/industry driven, not science-driven.
- When thinking about having to realize 10 Gen1 plants – which seems like a daunting task – keep in mind that the associated spending is 100 Billion per year.

This requires a dramatic change of the organization of the field: the funding structure, governance, human resource strategy. Involvement of industry.

Finally….if you want sustainable energy fast, it must not be durable.

- The long time scales of the energy transition really derive from the fact that the installations are meant to have a long life time. Energy is house-like, not toothbrush-like.

- A fast transition would require short-lived, cheap energy solutions. PV-paint on the roof of your house, that costs little and needs to be replaced every other year. As a business model, that is much more attractive. See: smart phones, laptops. Not: e.g. LED lighting.

- Fusion is at the other end of the spectrum: high up-front investment, expensive hardware that must operate for decades to earn back the investment.
This may prove to be the biggest hurdle for deployment of fusion energy.

- Therefore: emphasize smaller, simpler, sooner,….and cheaper: short-lived is good.

TU/e Technische Universiteit Eindhoven University of Technology