How the photovoltaic revolution will change global production and trade patterns

Ruggero Schleicher-Tappeser

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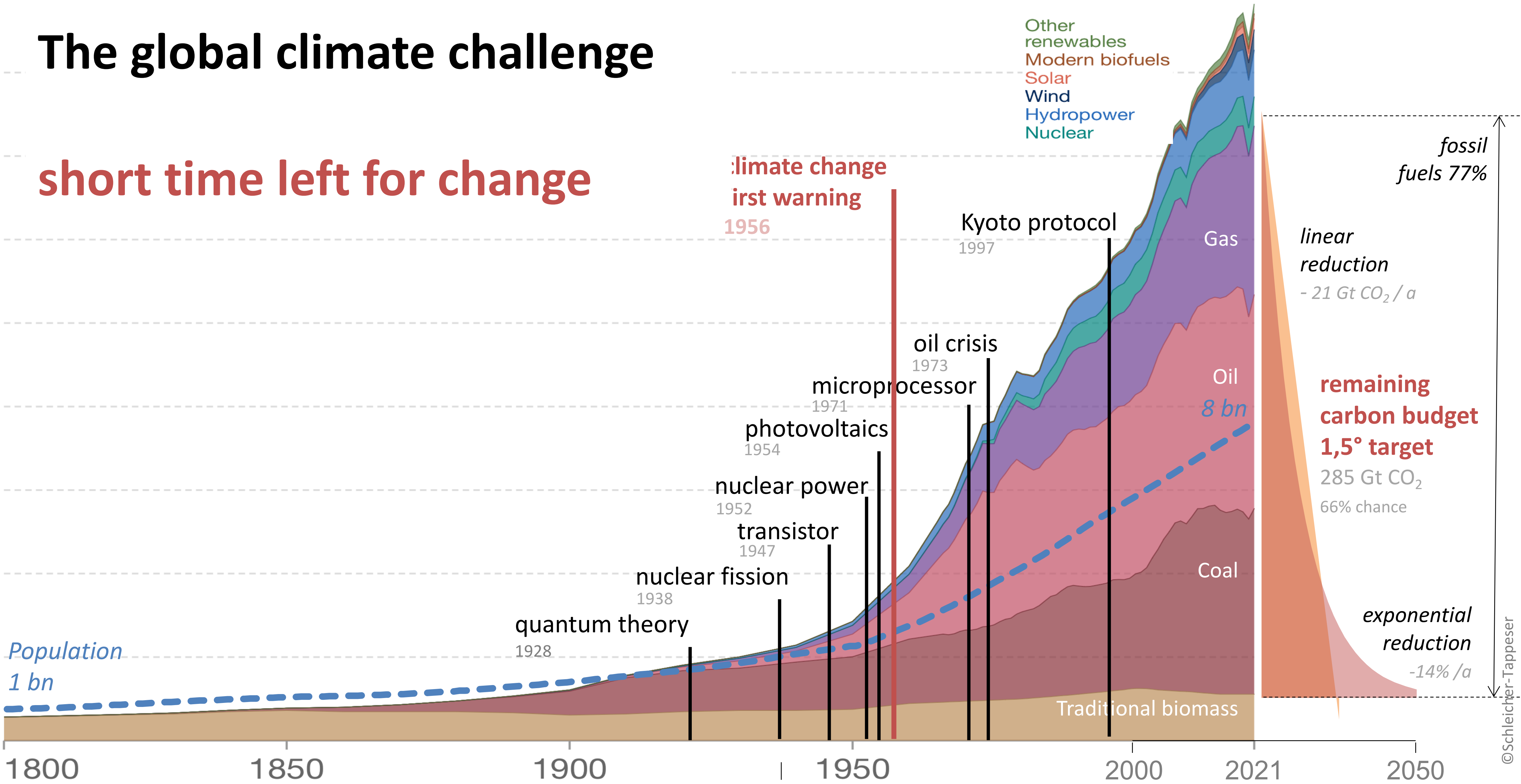
www.sustainablestrategies.eu

Outline

- The global climate challenge
- The future of energy supply is electric: turning away from fire
- PV will be the dominant source of energy
- The geography of cheap energy is dramatically shifting
- Consequences for a European industry policy
- Managing the transformation

The global climate challenge

short time left for change



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Useful energy we need

Elmag. Radiation /
Light

illumination,
communication
photochemistry

Electricity

communication,
computing,
controlling

different temperatures

Heat

heating,
transforming
materials

different molecules

Chemical energy

(food),
(chemical processes)

Mechanical energy

transport,
transforming
materials

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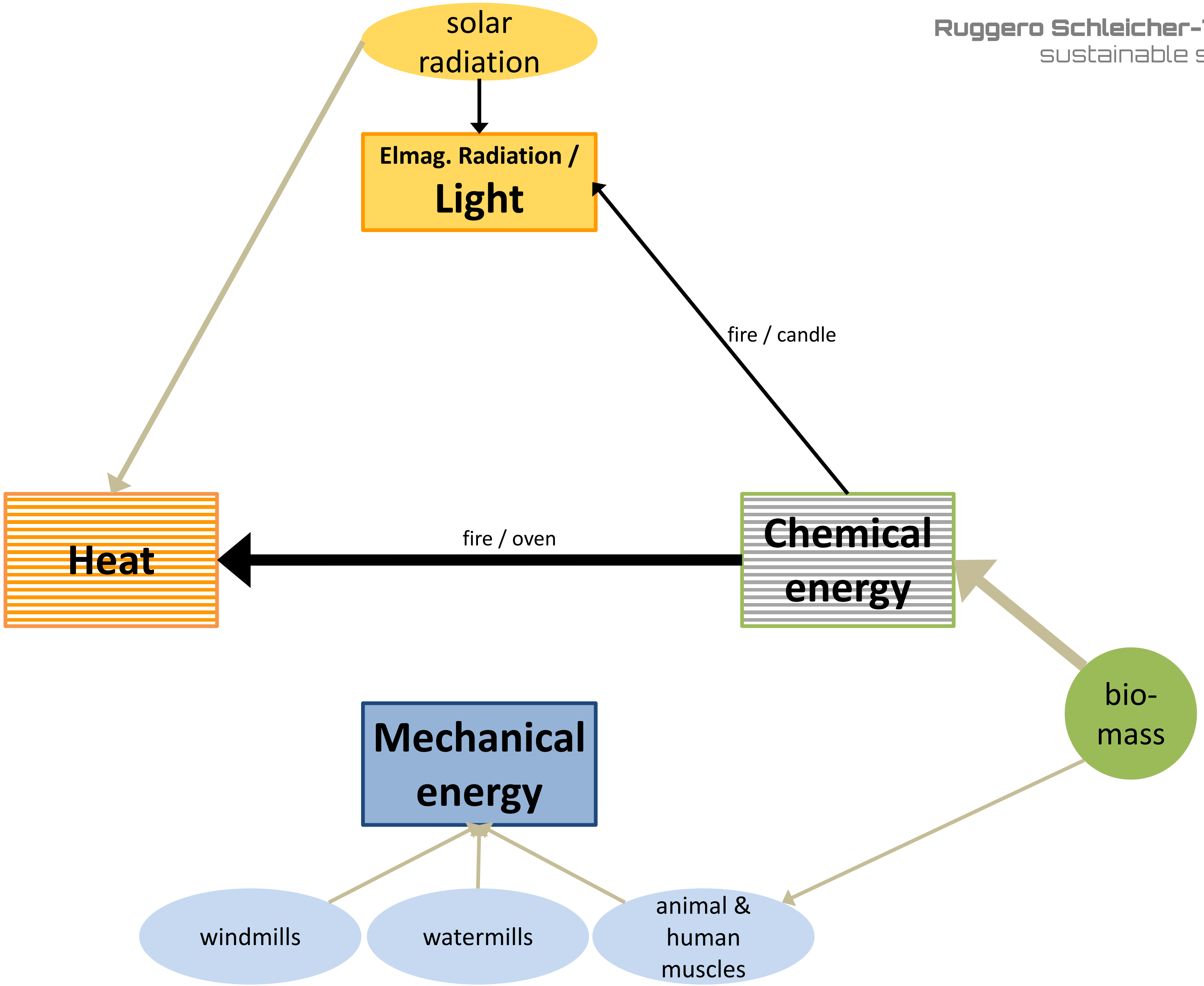
1700 - 1800



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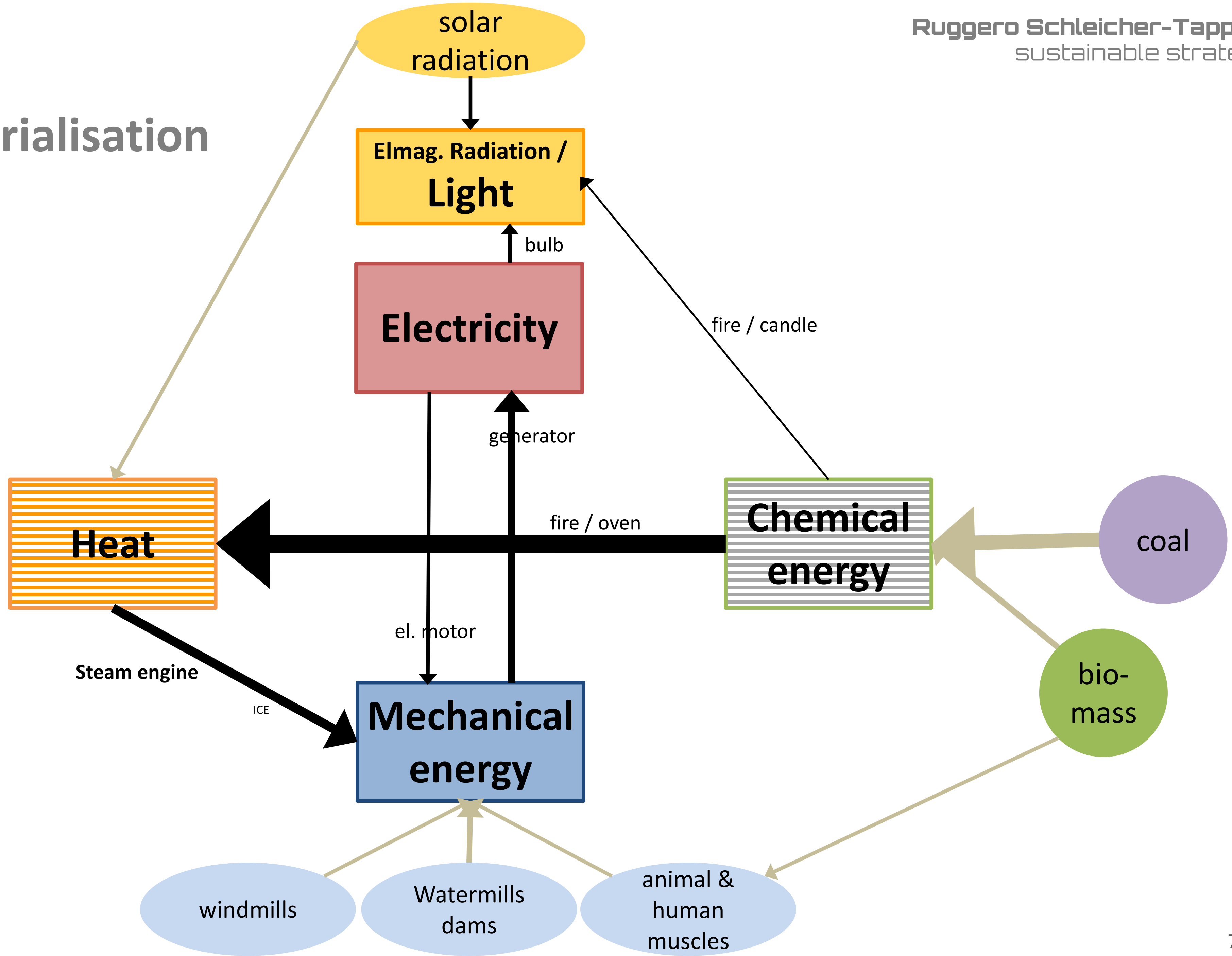
1800 - 1900
Start of industrialisation

Coal
- high energy density
- only in some locations
- transportable

→ Steam engine
- mechanisation
- railways, ships
- geographical expansion

→ Electricity
- telegraph, telephone
- flexible & small mechanical energy
- Illumination
- scientific challenge



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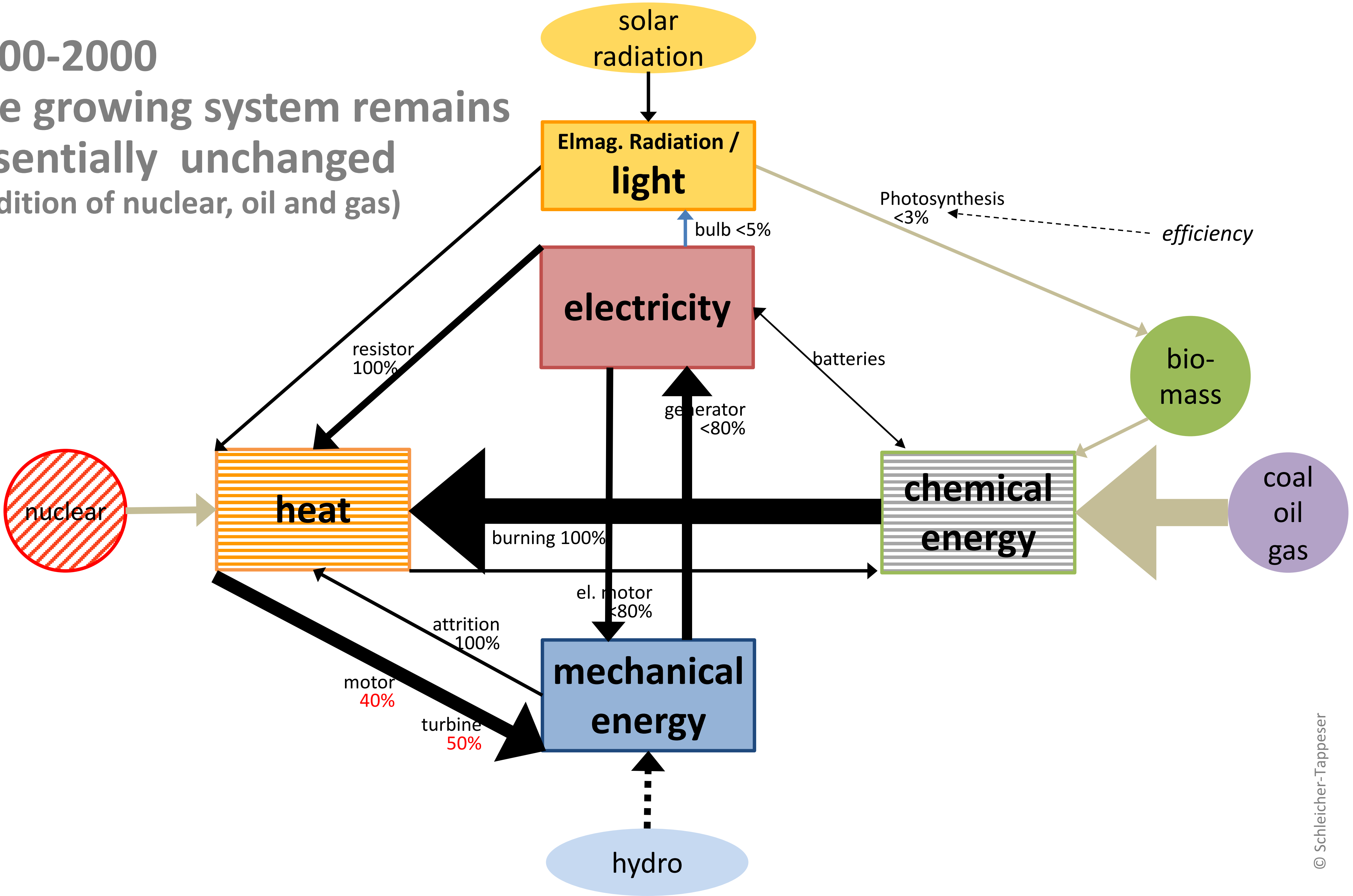
1900-2000
The growing system remains essentially unchanged
(addition of nuclear, oil and gas)



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1900-1938:
Upheaval in Physics: discovery of new laws & worlds at the atomic level

1900 Max **Planck** postulates that electromagnetic radiation is portioned into discrete “quanta”

1904 Albert **Einstein** postulates the equivalence of mass and energy in his Special Relativity Theory

1911 **Rutherford**’s atom model: a small positively charged heavy nucleus is orbited by negatively charged electrons

1926-28 **Heisenberg**, **Schrödinger** and **Dirac** develop a mathematical formulation of **QUANTUM THEORY**

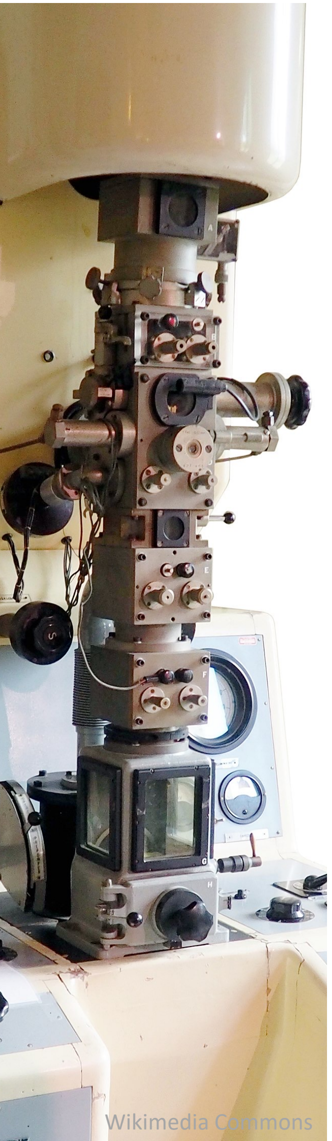
1938 Otto **Hahn** and Lise **Meitner** discover & explain nuclear fission

- Macro world ←→ Nano world: continuous properties & processes ←→ Quantised states & changes
- particle/wave duality, waves as probabilities
- the observer is part of the system
- ➢ counter-intuitive laws at the nano-level

1945 →→
Discovery of new dimensions

- material sciences
- electronics
- informatics
- molecular biology
- quantum chemistry
- geophysics/climate science
- …

After 1950: Nanosciences bring new technologies
RESEARCH and INFORMATION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New measurement methods and instruments
→ discovery of nanoworlds

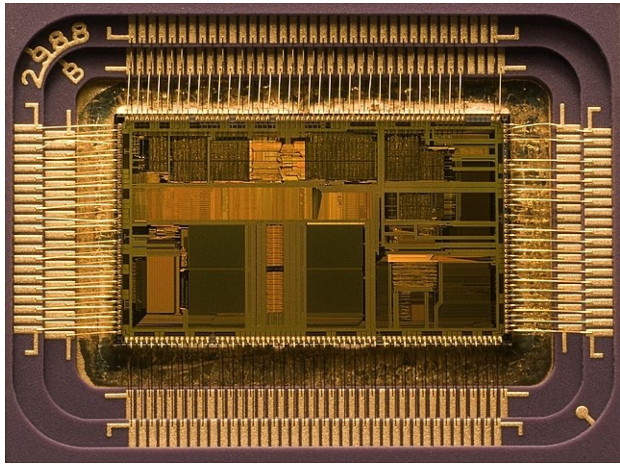
- Mass & other spectrometers
- Electron & X-ray microscopes
- Magnetic resonance imaging
- Sensors for chemicals
- Image sensors
- Positron Emission Tomography
- …

Transistor → Microelectronics → Digitalisation

1971: Microprocessor with
8,000 Transistors

2021: Microprocessor with
80,000,000,000 Transistors

Boost for all other technologies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DNA structure → Microbiology → Gene technology

1953: Discovery basic DNA structure

2021: mRNA vaccine beats Covid


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Information processing increasingly decoupled from matter and energy

– **miniaturisation** saves energy, material and costs → boost in performance

– **increase in speed** saves energy, material and costs → boost in performance

Nanosciences bring
KEY NEW ENERGY TECHNOLOGIES

Photovoltaics

Power generation

- Direct generation of electricity from sunlight
- >20 times more efficient than photosynthesis
- Lowest electricity costs
- Decentralised generation
- Fluctuation with solar radiation

Power Electronics

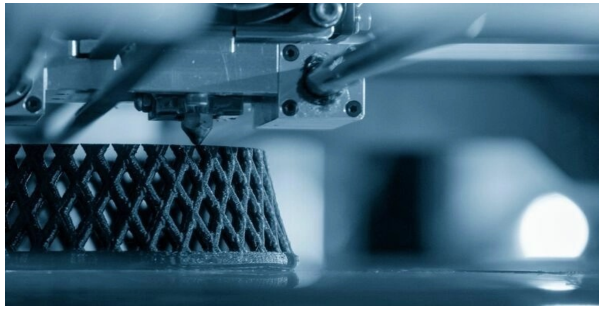
Power transformation, transport and control

- Electricity converters
- Wind power to grid
- Digital control of electricity systems
- Efficient grids, HVDC, superconductors
- Digital frequency control → efficient e-motors

Batteries

Power storage

- High-density electro-chemical battery cells
- Flow batteries for longer-term-storage
- Strong density improve-ments and cost reduction
- Fuel cells
- Improved electrolysers



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Electricity → Radiation

Material processing & Light

- LED, Laser, Microwave…
- 3D-printing: up to 75% material savings
- High life-cycle energy savings
- Efficient decentralised small series production

Very rapid performance boost and cost reduction well above macroscopic process learning curves: miniaturisation and speed/efficiency increase due to improved processes at nanoscale

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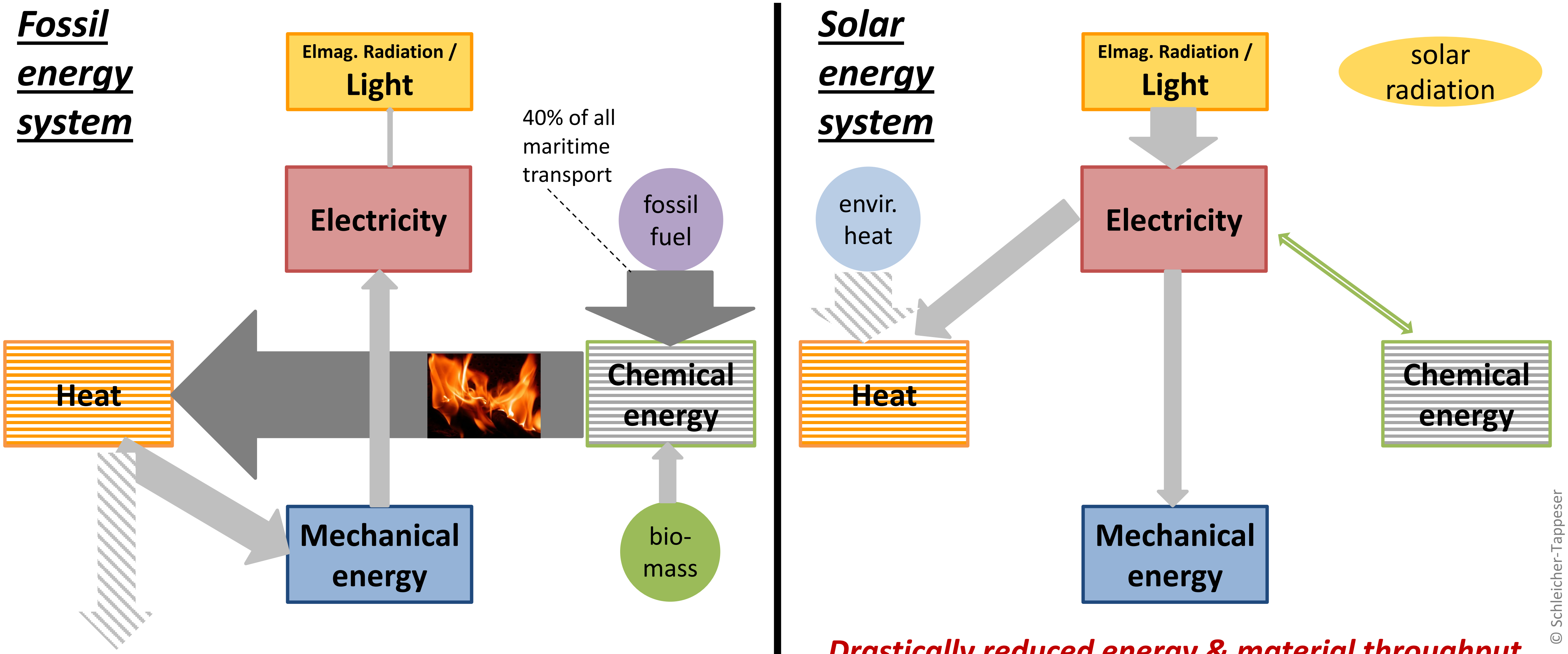
A fundamental paradigm shift
Abandoning fire as basis of our civilisation
Huge gains in energy and material efficiency



Drastically reduced energy & material throughput

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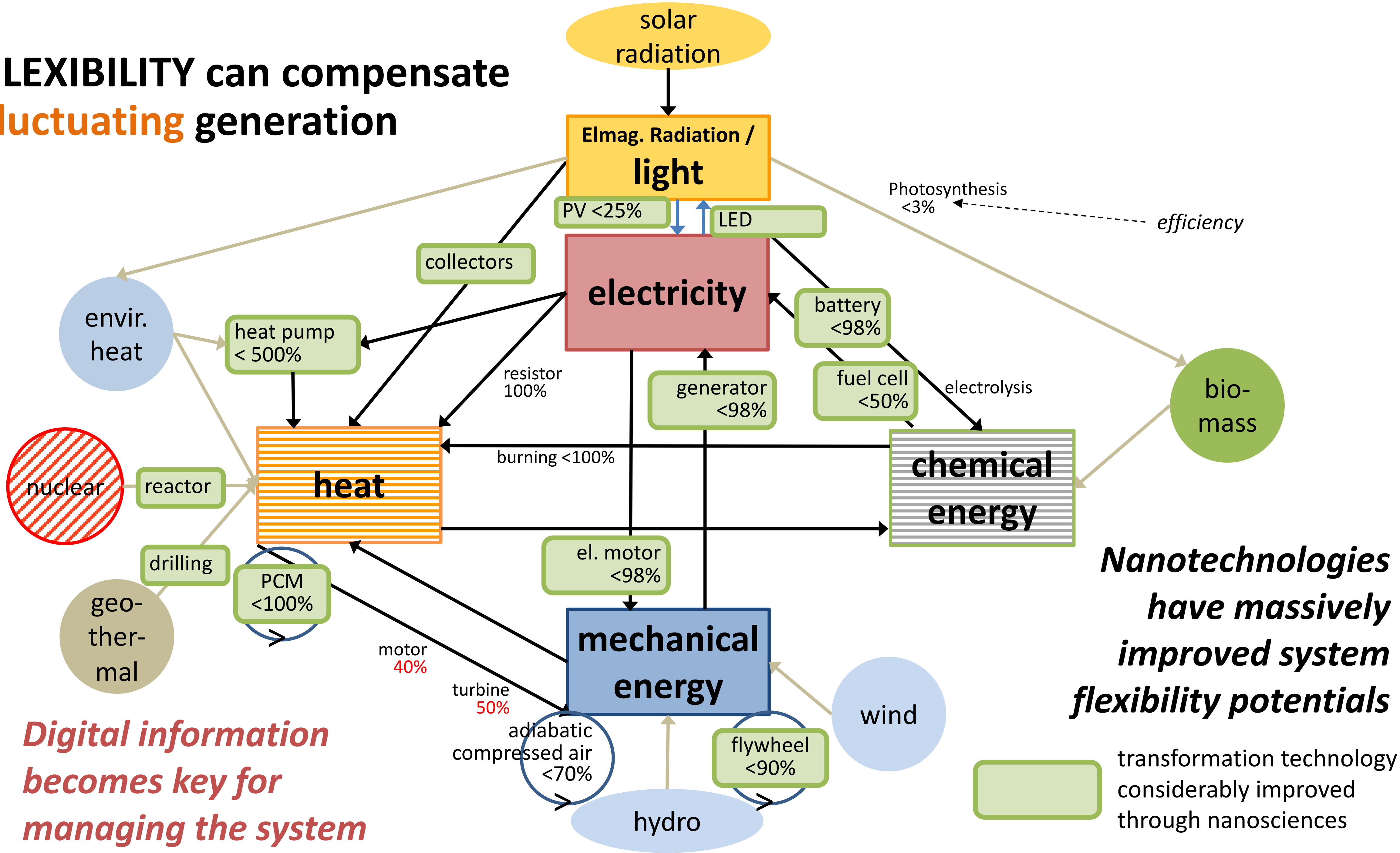
FLEXIBILITY can compensate fluctuating generation



Nanotechnologies have massively improved system flexibility potentials

Digital information becomes key for managing the system

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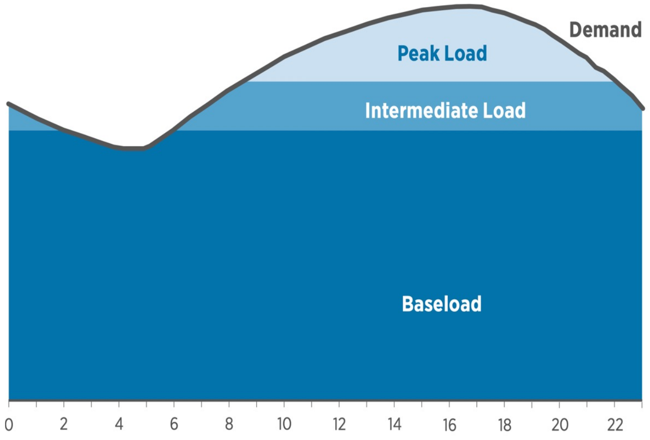
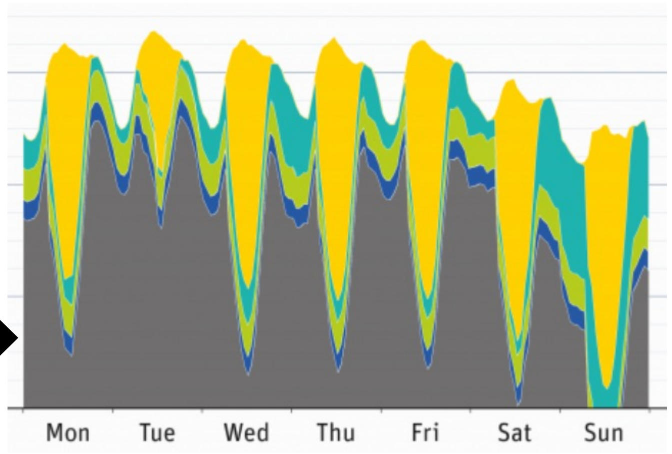
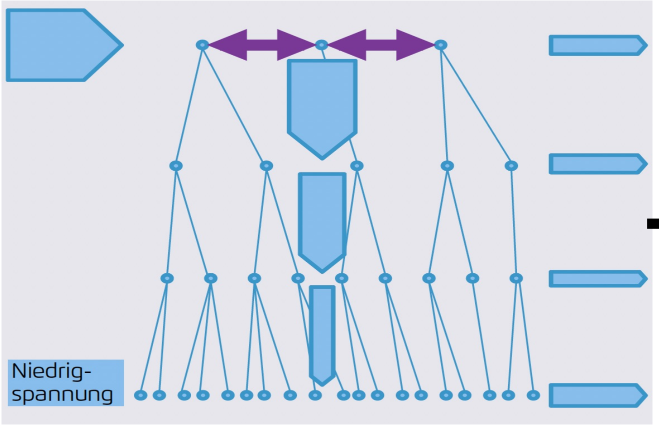
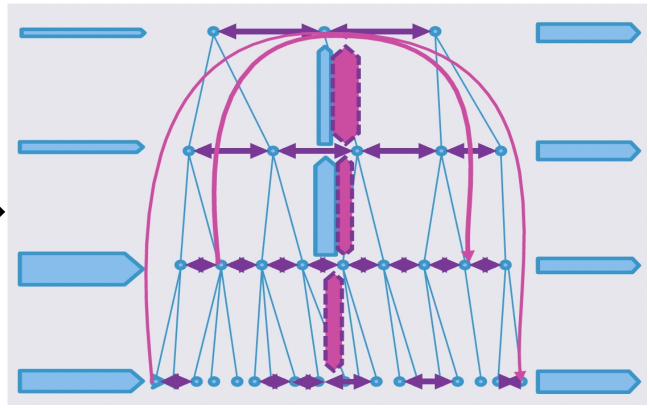
Flexibility sources allow full coverage with renewable electricity

Flexibility source	New technologies
Demand side management	power electronics, communication
Flexible generation	power electronics, materials
Energy storage	batteries, hydrogen conversion, power electronics
Sector coupling	power electronics, heat pumps, electric transport
Grids: Transmission & distribution	power electronics, digitalisation, superconductivity
Bottom-up system control logic	power electronics, local energy markets









Calculations show: Combinations of these approaches can guarantee a fully renewable energy supply in Europe and the US at lower costs

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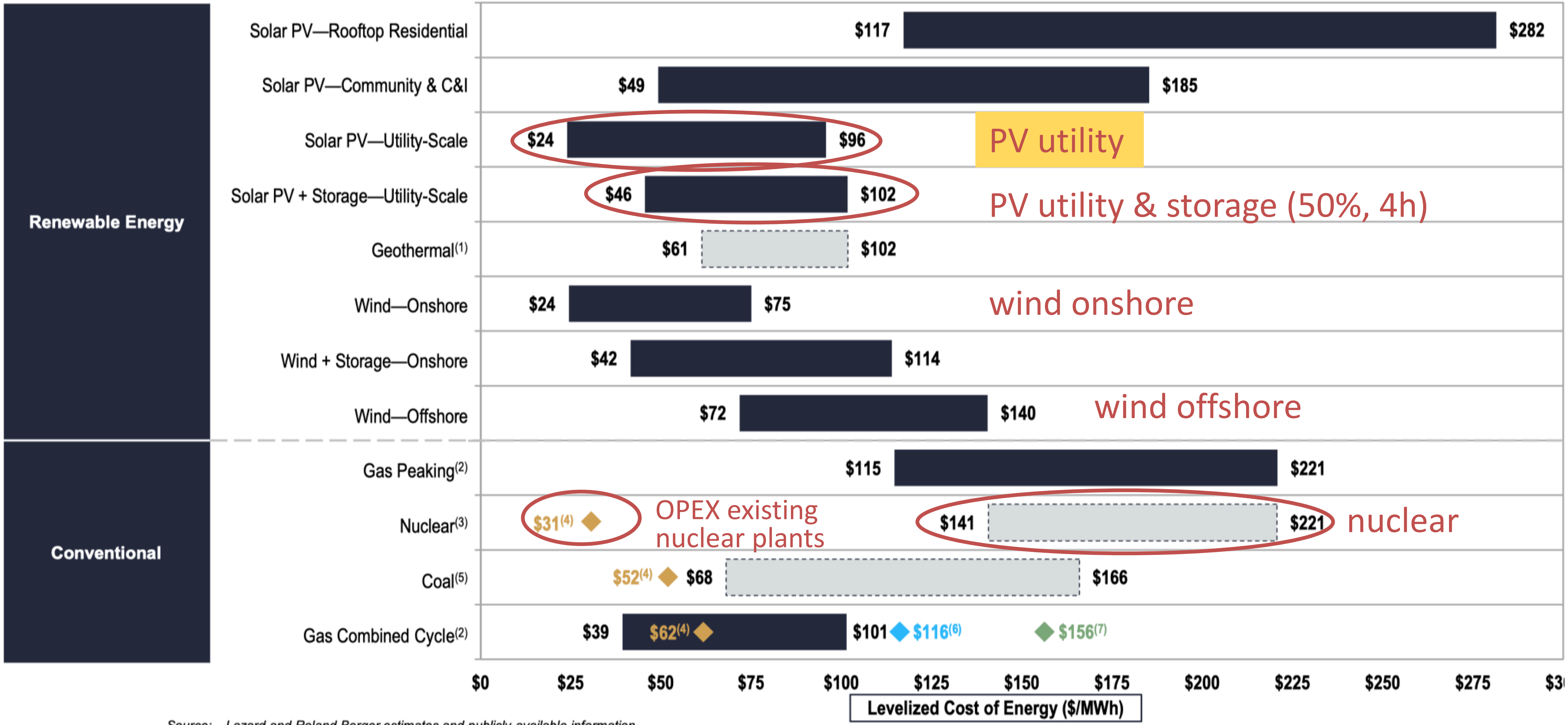
2023

Levelized Cost of Energy Comparison—Unsubsidized Analysis

Selected renewable energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances



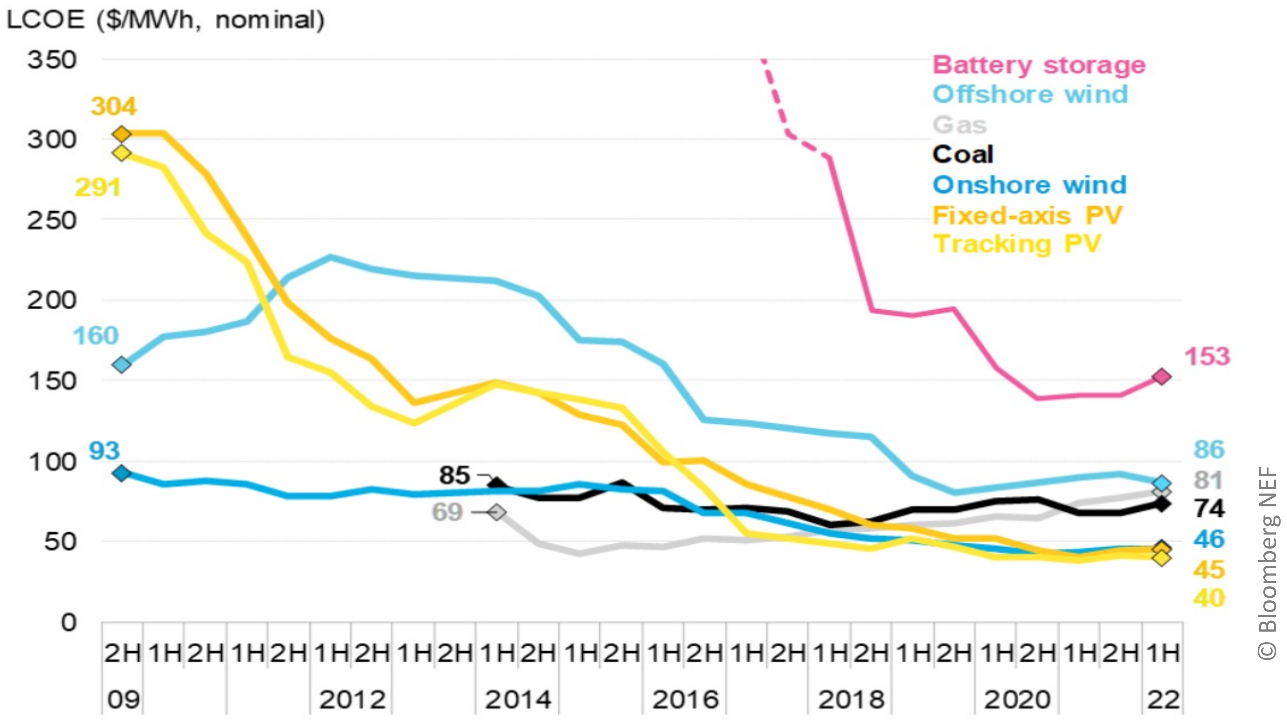
Source: *Lazard and Roland Berger estimates and publicly available information.*

Note: Here and throughout this presentation, unless otherwise indicated, the analysis assumes 60% debt at an 8% interest rate and 40% equity at a 12% cost. See page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities.

Photovoltaics are unbeatable due to nanoscience: Cost reduction stronger than in all other energy sources

1. **Extremely reliable.** No moving parts, no fuel, very low risks. Last for 30 to 40 years
2. **Mass production.** Classical economies of scale. New factories: 50 million modules per year
3. **Rapid innovation at nano-scale.** 2010-21: module efficiency 14%→ 22%
4. **Extremely scalable, up and down.** Energy transformation occurs at nano-level
5. **Rapid deployment.** Factories 2a, plants ½ a → 10 x shorter innovation cycles
6. **Strong potential for further cost reduction.** Perovskite cells , material reduction with BIPV

- No other energy source has matched efficiency gains, cost reductions and growth rates of PV
- **Nanotechnical innovation is the main driver for the extraordinary cost reductions – mass production experience comes only second**



Cost reduction factors reveal the potential of different technologies

Cost reduction factors:

- **Standard learning curve** for non-mature products
- Enhanced learning: high numbers of **small modules**
- Nanotechnical innovation → **efficiency improvement**
- Cost reduction of **innovative input materials**
- **Design improvement** reducing material intensity

>50% of PV panel cost reduction due to nanoscience innovation:

- **Efficiency** improved → smaller surface & surface related costs
- **Semiconductor thickness** reduction
- **Semiconductor cost** reduction
- **Low-light** & **high-temperature** behaviour improved
- Longer **lifetime**

Compare: Wind has only limited cost reduction potential:

- Efficiency gains came through design change: higher towers → more wind
- Very limited nanotechnical cost reduction potential:
- Limited potential for large series production
- Long innovation cycles
- **High material intensity** with cost risks: Onshore wind needs 1,5x more steel and 5x more concrete than utility PV. Offshore is worse.

Technologies with a large share of costs in mature com-ponents (e.g. heat turbines in CSP) are doomed to fail

PV and system change – strong resistance for 50 years

EXAMPLES

1973: **Nixon**'s national energy research plan: no PV despite potential

1981: **Reagan** and U-turn of oil industry kill fledgling PV industry

2000: Introducing feed-in-tariffs: Success required parallel action to established structures

2009: Foundation process of **IRENA**: tedious

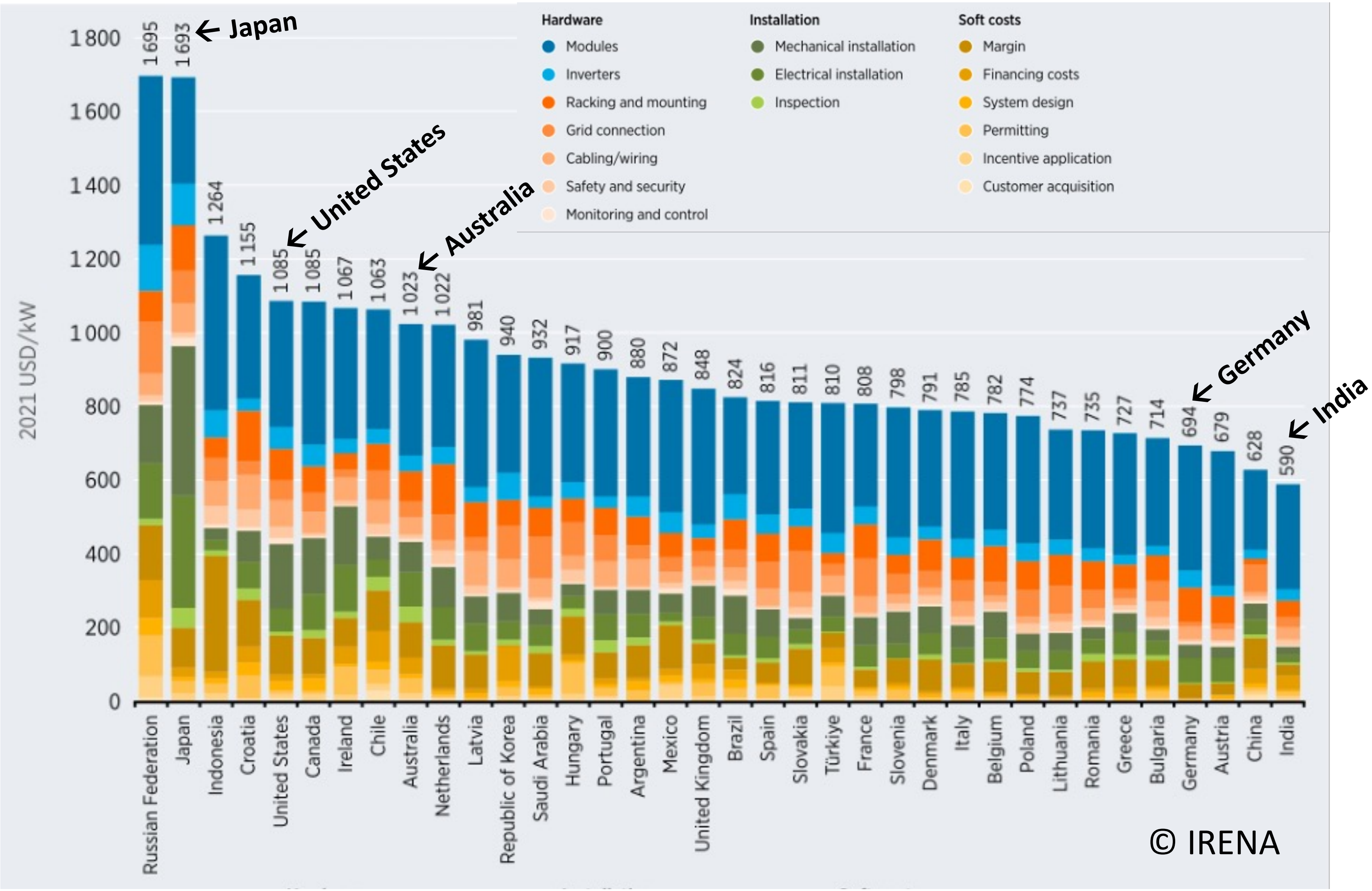
2011: European **governments slash PV** surge, 120'000 jobs lost in D

2014: No chance for large PV industry in Europe – **French-German xGWp** project fails

2008→**China** did not play by the big boys rules → 80% of global market, 34% of installations

2022: The **hydrogen hype**

Politics make a difference:
The example of installation costs



2021: A solar power plant in Japan costs 2,9 times as much than the same plant in India.

In Germany only 1,2 times as much.

Free markets? No technological bias?

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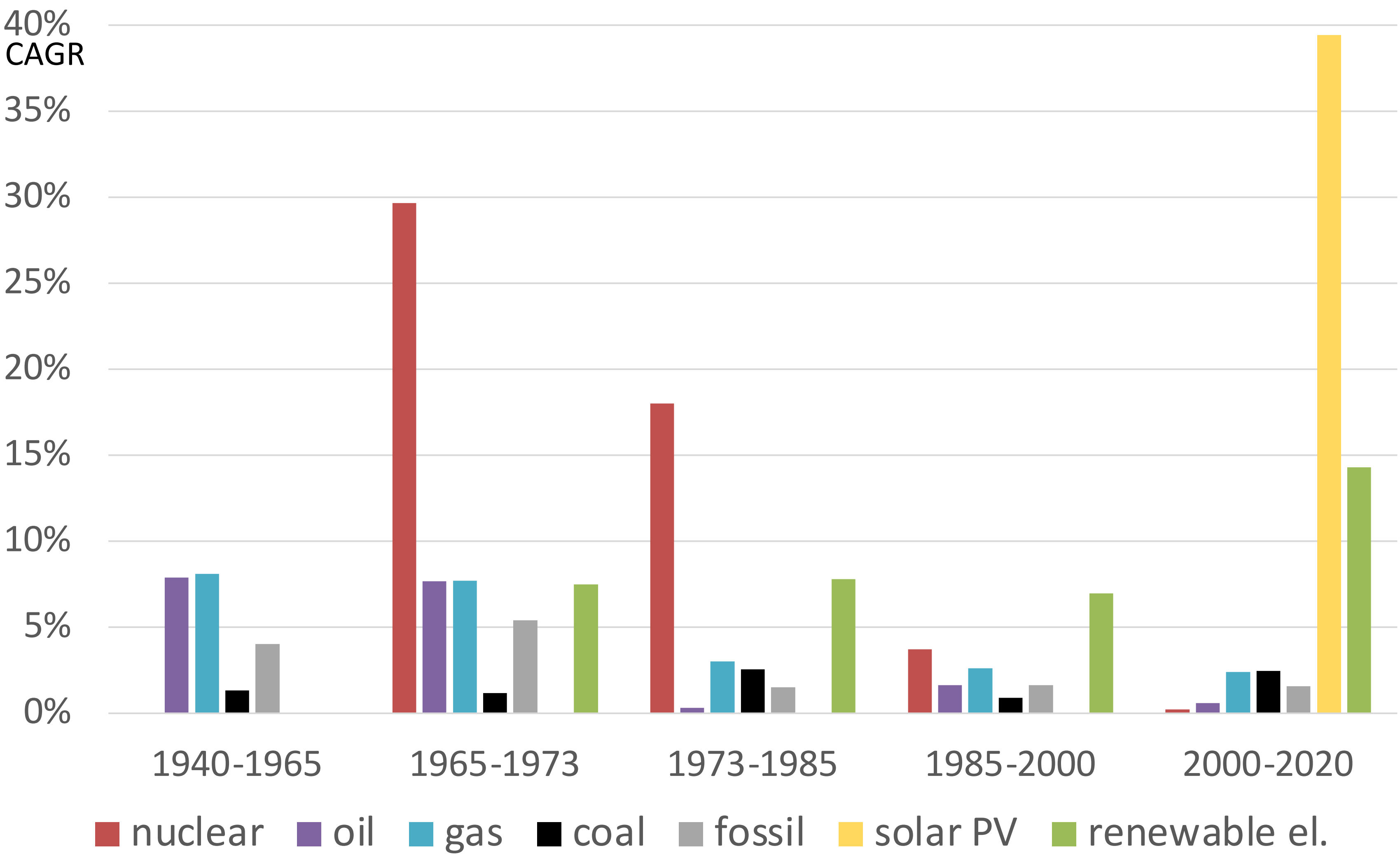
Despite all: Growth patterns have shifted



- After oil crisis 1973, oil growth drops sharply from over 7% to 0,9%
- Nuclear growth drops with delay after 1979 TMI nuclear accident
- Solar grows sharply after 2000
- After growth drop in 1990, coal restarts to grow faster around 2000

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Data: bp energy statistics, Our World in Data

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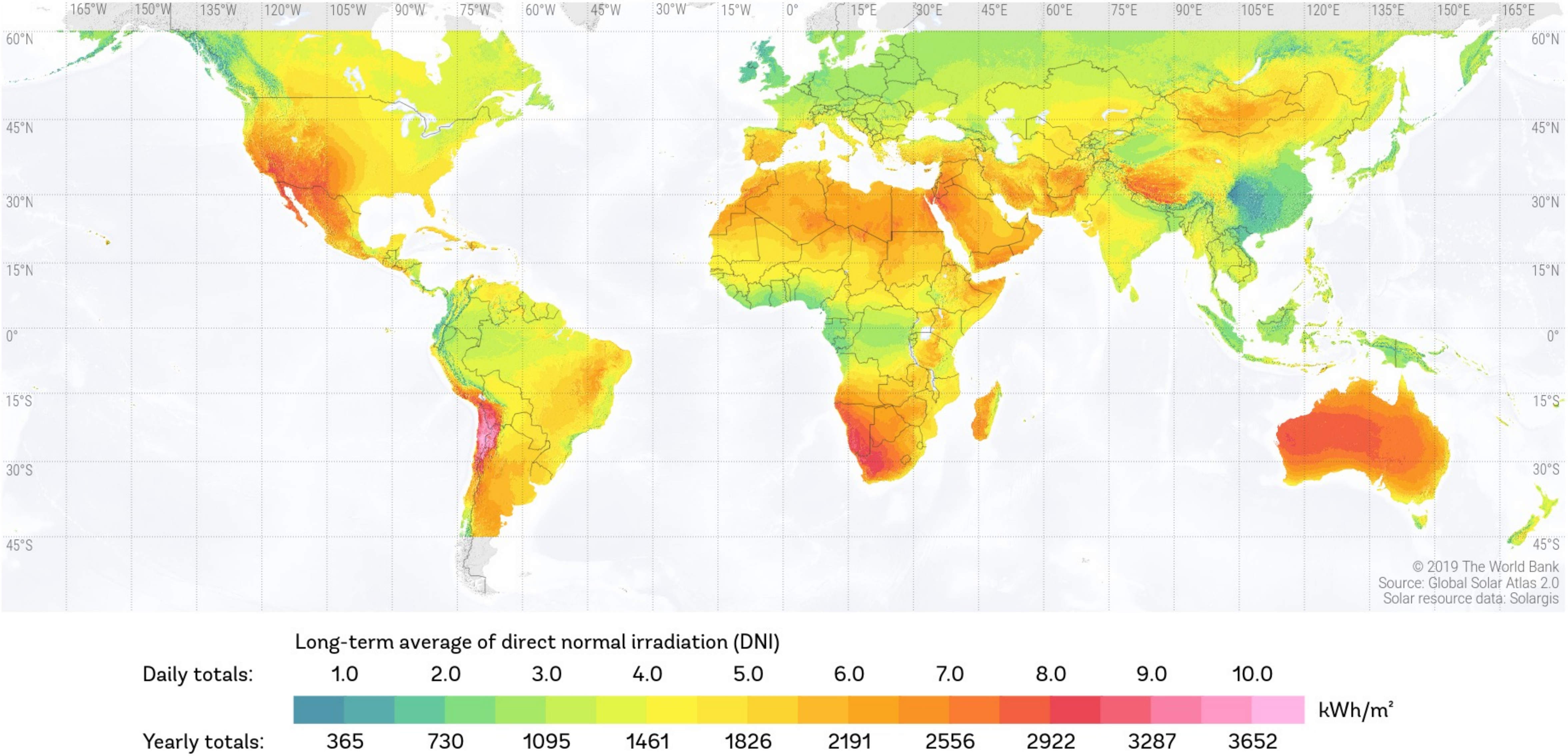
SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION

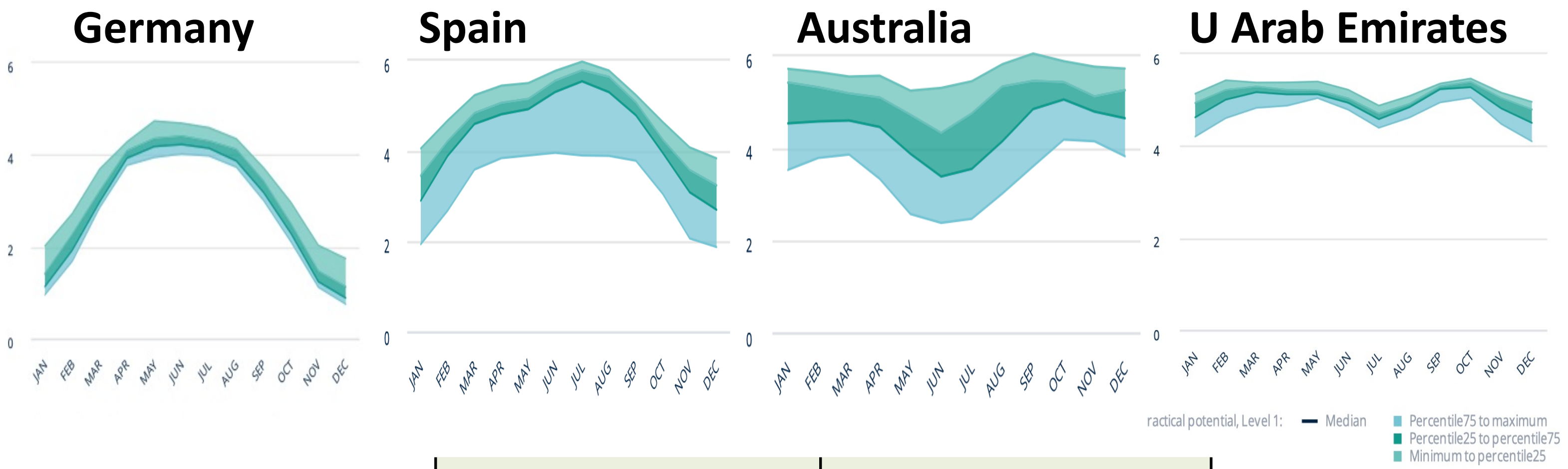
WORLD BANK GROUP ESMAP SOLARGIS



This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info.

If PV is the cheapest energy source → SEASONALITY is a challenge for energy-intensive industries

MONTHLY VARIATION OF PV POWER OUTPUT:



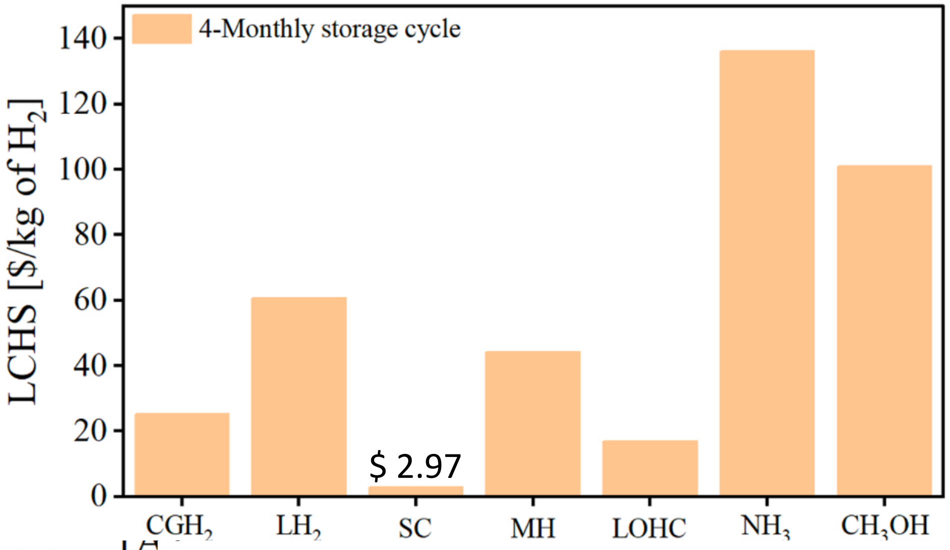
	average yield [kWh/kWp]	seaso-nality max/min month	factory capacity: best month yield Power utilisa-tion	Factory utilisa-tion	Yield/D	yearly average yield Power utilisa-tion	Factory utilisa-tion	Yield/D	weakest month yield Power utilisation	Factory utilisa-tion	Yield/D
Germany	2961	4,37	100%	61%	**1,00**	80%	80%	**1,00**	37%	100%	**1,00**
Spain	4413	1,93		76%	1,49	90%	90%	1,67	68%		2,73
India	4322	1,75		79%	1,46	91%	91%	1,67	73%		2,85
Brazil	4404	1,34		87%	1,49	95%	95%	1,77	85%		3,41
Australia	4707	1,47		84%	1,59	94%	94%	1,87	81%		3,46
UAE	5004	1,18		92%	1,69	97%	97%	2,06	92%		4,16

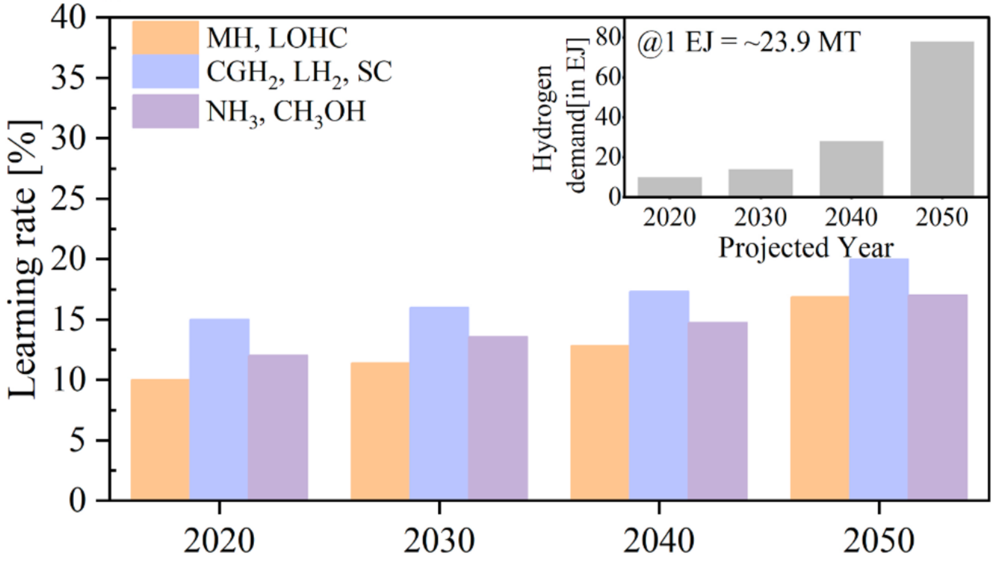
- **High capital cost in industry calls for continuous operation**
- Daily variations can be buffered with heat and electricity storage
- Strong seasonal variations → low yield in weakest month

→ Comparing **Germany** with southern countries: **big disadvantages**

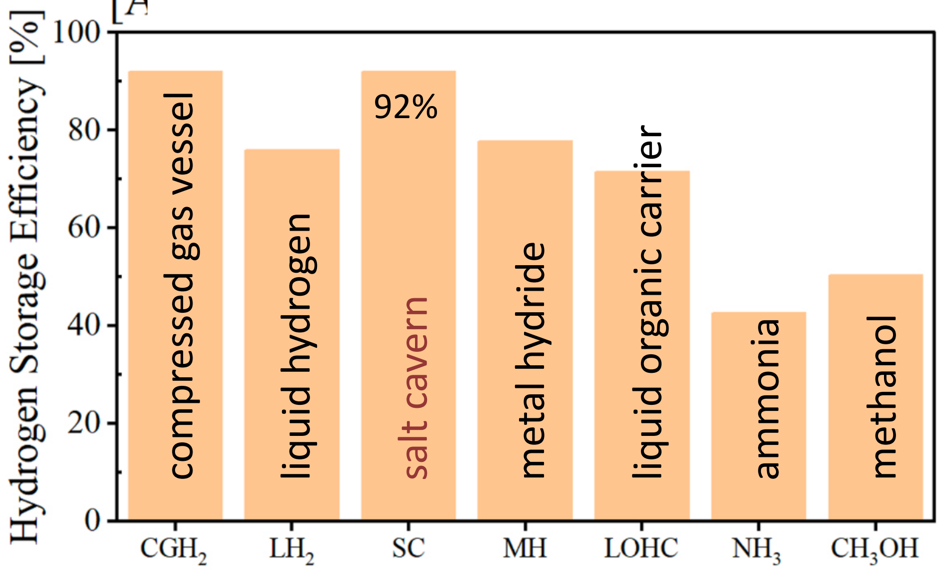
- Wind may alleviate problems but is increasingly more expensive than PV

Hydrogen Storage





© [Abdin et al. 2022](#)
see also [Zivar et al. 2020](#), [Capellani 2022](#)



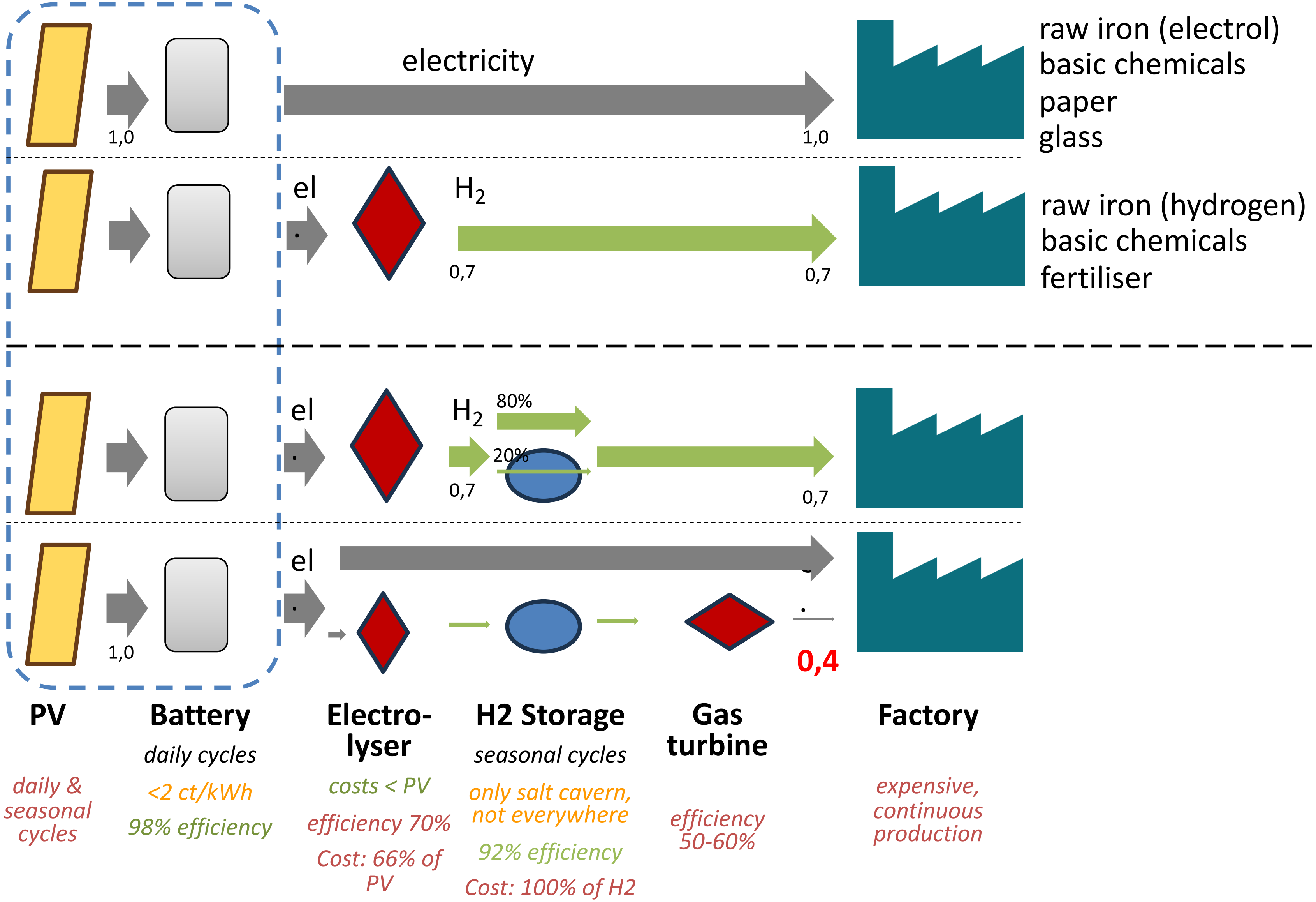
"The findings of this study show that Underground Hydrogen Storage, like other storage systems, is still in its infancy"
[Muhammed et al. 2022](#)

- Present green hydrogen costs: \$3.20 – 7.70/ kg H_2

→ **salt cavern storage is the only solution to be considered**

- Salt cavern storage is available only in rare locations, e.g. Germany ***, Britain**, France*, Poland*
- SALT CAVERN STORAGE for 6 months – if available – would roughly double green hydrogen costs

Hydrogen salt cavern storage brings improvement – But costs in central Europe remain much higher compared to the south



	UAE	Spain
Electricity	**100%**	**150%**
H2	**100%**	**150%**
	relative costs	

100% factory utilisation, no storage

	Germany
H2	**190%**
	(storage 20%)
Electricity	**330%**
	(storage 30%)
	relative costs

100% factory & PV utilisation

storage optimised

own calculations

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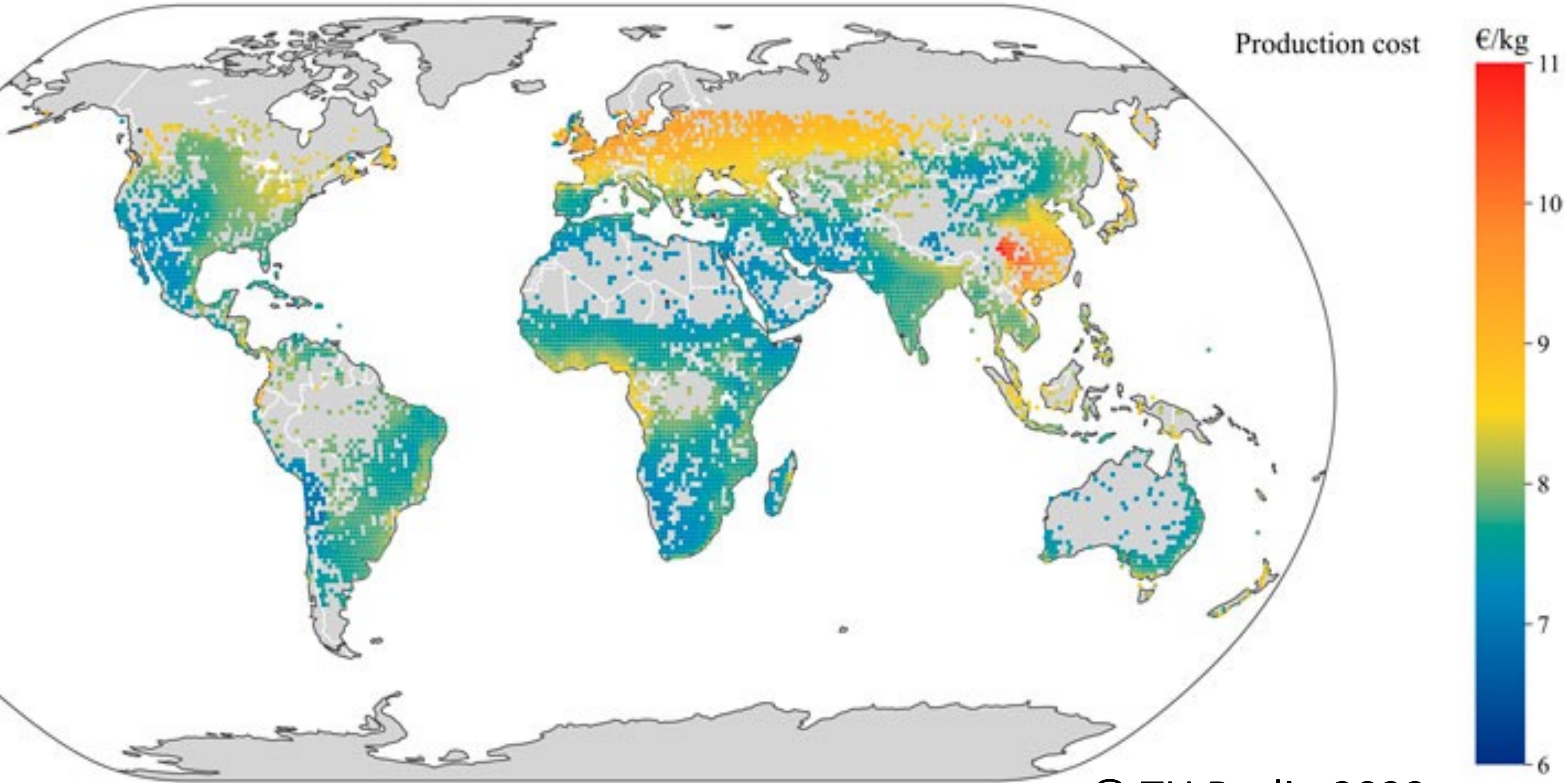
Hydrogen production costs in 2030:
Calculation results vary strongly : one example



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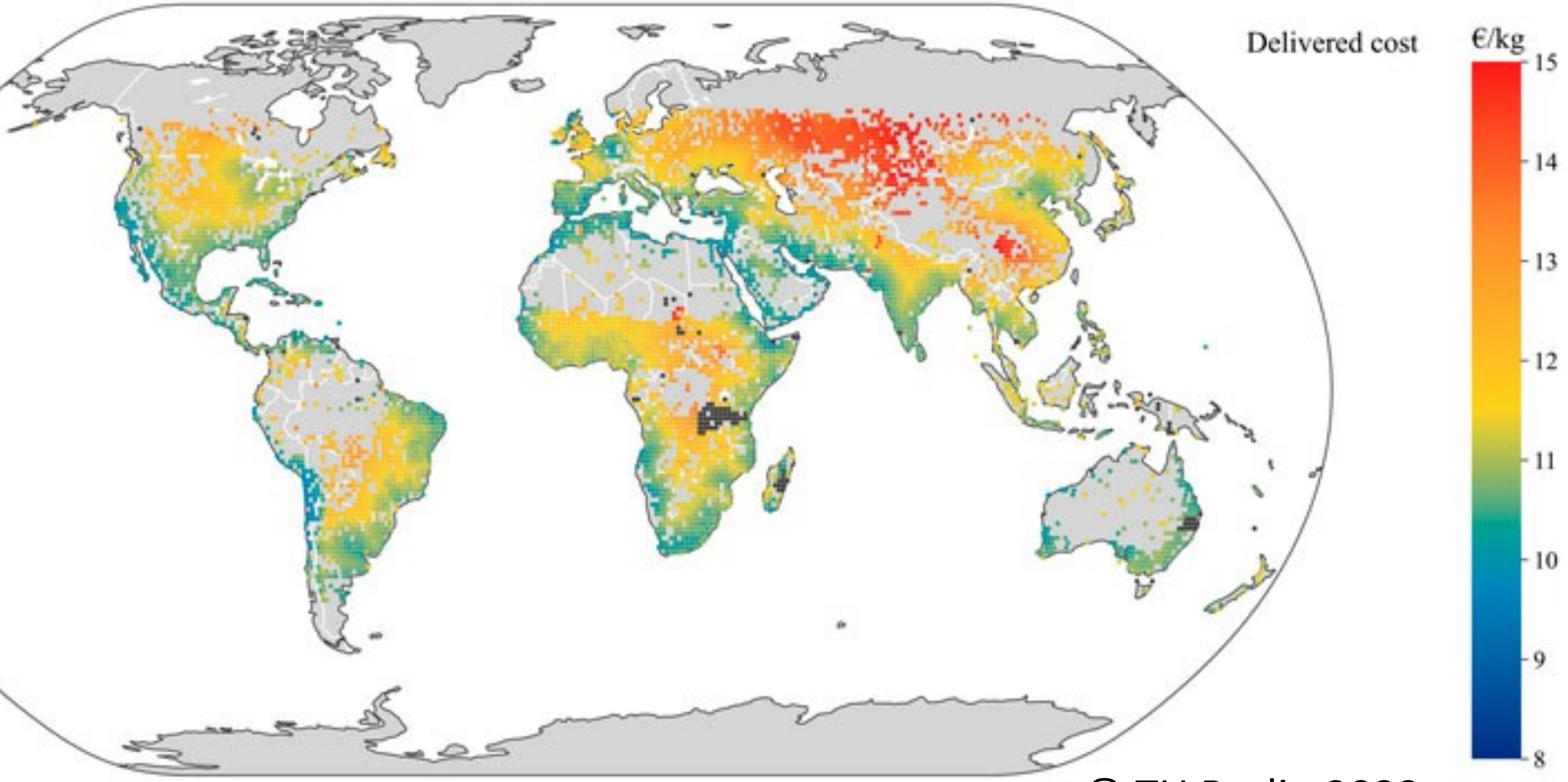
7€/kg =

0,175 €/kg_{H2} =

0,35 €/kWh_{el}

Hydrogen costs – imports delivered to Cologne/ Germany

Optimistic assumptions – import cheaper than local production



strongly diverging assumptions on transport efficiencies & costs due to missing experience & strong lobby influence

10€/kg =

0,25 €/kg_{H2} =

0,50 €/kWh_{el}

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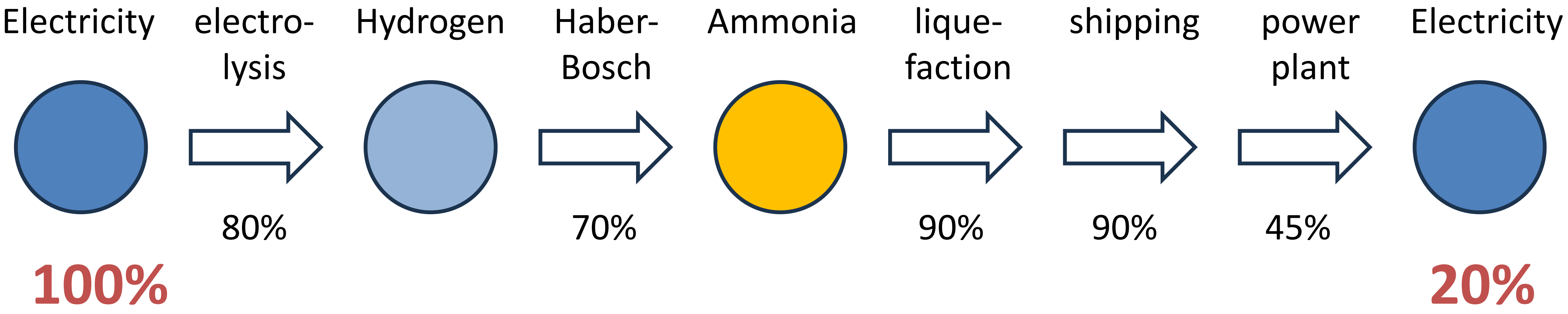
An example for the many illusions presently discussed: Electricity from imported ammonia



→ Electricity from imported ammonia costs much more than <u>five times</u> the original price

For peaker plants that may be acceptable in small amounts.
Ammonia is toxic, but direct combustion is cheaper than re-conversion to H_2.
Presently this is the preferred outlook for ships.

In the long run: subsidies cannot cheat physics

Data: Liebreich 2022

European competitiveness for energy-intensive industries is declining

Germany: relative energy costs

- Pipeline transport from the Middle East cheapest import source of hydrogen
- Cost of continuous supply (local or import) compared to good solar locations

Hydrogen 150% – 190%

Electricity > 300%

Electricity is cheaper for most applications

Raw materials often originate in regions with cheap energy

- Metal, especially steel
  - Australia, USA, Ukraine…
- Chemical feedstock: oil, gas, coal, biomass
  - Middle East, USA, India, China…
- Nitrogen for fertilizers is
  - Ubiquitous

Transporting raw materials is much more expensive than transporting products

Persistent and worsening disadvantages for energy-intensive industries in central and northern* Europe

*Hydroelectricity may provide some exceptions

Electricity transport across the Mediterranean: FOR ELECTRICITY: MUCH CHEAPER THAN TRANSPORTING HYDROGEN

- Greece-Egypt project 2023:
  1370 km, 3000 MW, 500 kV DC, Capex: M€ 3500.
  → over 25 years: 0,005€/kWh_{el}
- Alassi et al. 2019:
  2000 km, 6000 MW, 800 kV DC, Capex + losses: M$ 2100
  → over 25 years: 0,002€/kWh_{el}
- Xlinks Morocco – Britain project 2022
  3800 km HVDC + PV + storage
  electricity sales price: 0,067 $/kWh
- IEA in Hydrogen transport cost comparison
  1000km 2$/$kgH_2$
  → converting H_2 in power: transport costs 0,10 $/$kWh_{el.}$ **Ridiculous**!
  No other HVDC cost figure to be found in IEA documents

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Politics is powerful
It can maintain structures beyond economic rationality over decades

Worldwide fossil fuel subsidies: 6,8% of GDP

- Germany: Subsidies per emitted CO2 are higher than emission permit costs

Coal industry in Germany

- Hard coal subsidies since the sixties: € 200-300 bn
  Coal workers in 1960: 200’000

Nuclear power in France

- Macron emphasises the strong link between civil and military nuclear power
- EDF re-nationalised after a debt of 65 bn

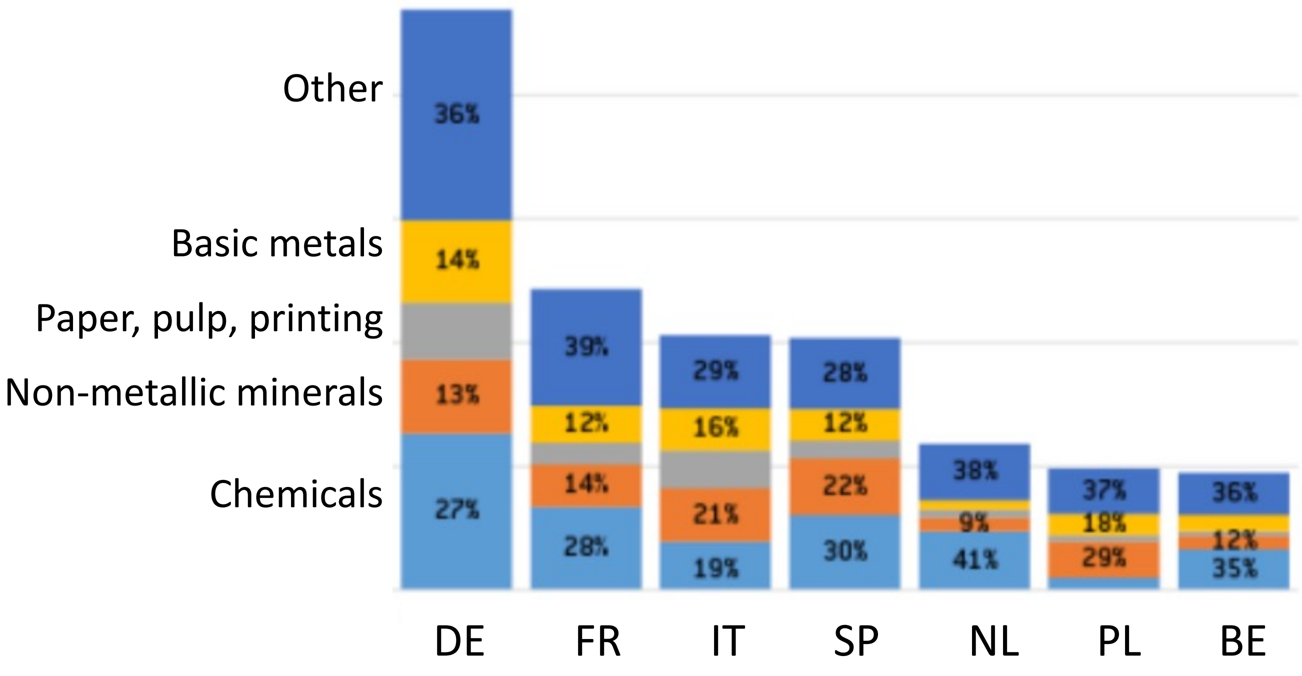
Biomethanol additions to gasoline in Germany

- Biofuel cultures: 1% of road transport energy.
- The same surface with PV could cover the entire German electricity consumption

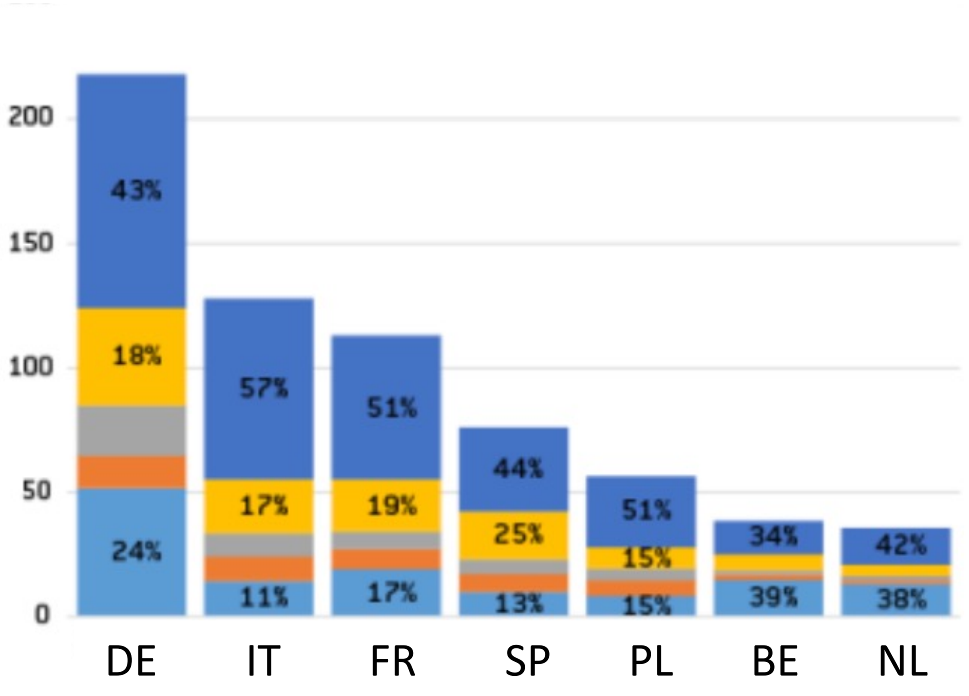
Energy intensive industries are capital intensive and need continuous operation

- Germany dominates the European industrial energy consumption
- A few sectors make up for over 60%

2020 Industrial gas demand



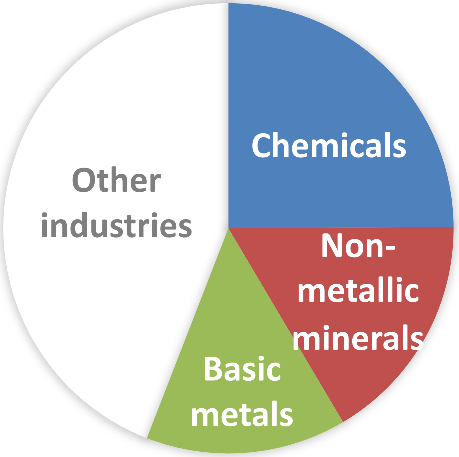
Industrial electricity demand



© Bruegel *based on Eurostat*

Energy-intensive industries in Europe
huge subsidised energy consumption – small economic importance

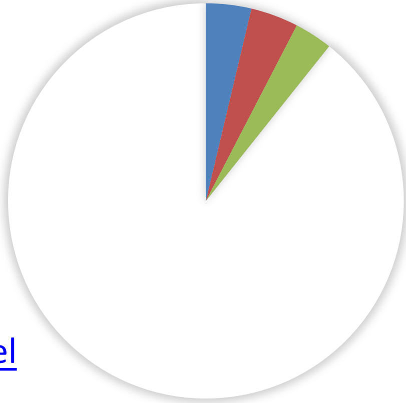
INDUSTRIAL GAS DEMAND



INDUSTRIAL POWER DEMAND

EMPLOYMENT MANUFACTURING

GROSS VALUE ADDED MANUFACTURING



Data: Bruegel

- Considering subsectors, the effect is even much stronger
- Germany: Decarbonising steel production with local green hydrogen would require increasing electricity production by 20%
- Easily transported and traded internationally:
  - Iron sponge or raw steel
  - Other metals (copper, aluminium…)
  - Ammonia-based fertilizer
  - Many basic or intermediate chemicals (others are too dangerous to transport)

Getting rid of energy-intensive industries → cheaper energy for SMEs and households

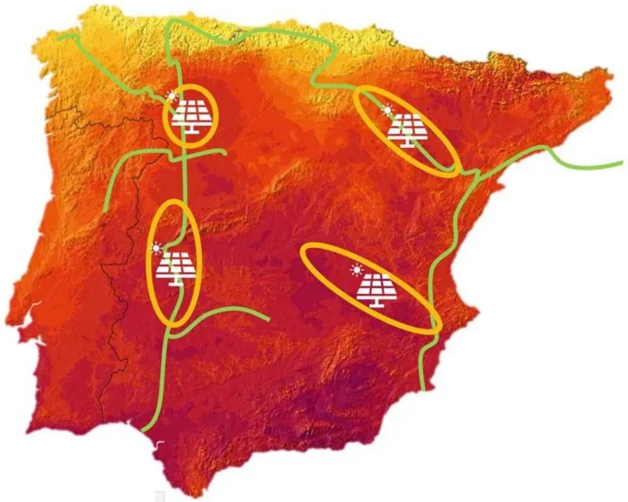
Green steel production emerging in favourable geographies

Steel and ammonia in Spain: HyDeal

- 4,8 GW PV, 3,3 GW Electrolyser, start 2028
- offtake by steel and ammonia industries
- hydrogen pipeline backbone

HyDeal España's PV areas

Land secured in area with high power potential and injection points into H_2 backbone



HyDeal España's customer base

Focused on major H_2 consumption clusters in Northern and Eastern Spain

Tata Steel and ACME project in India (Orisha) for greening steel production

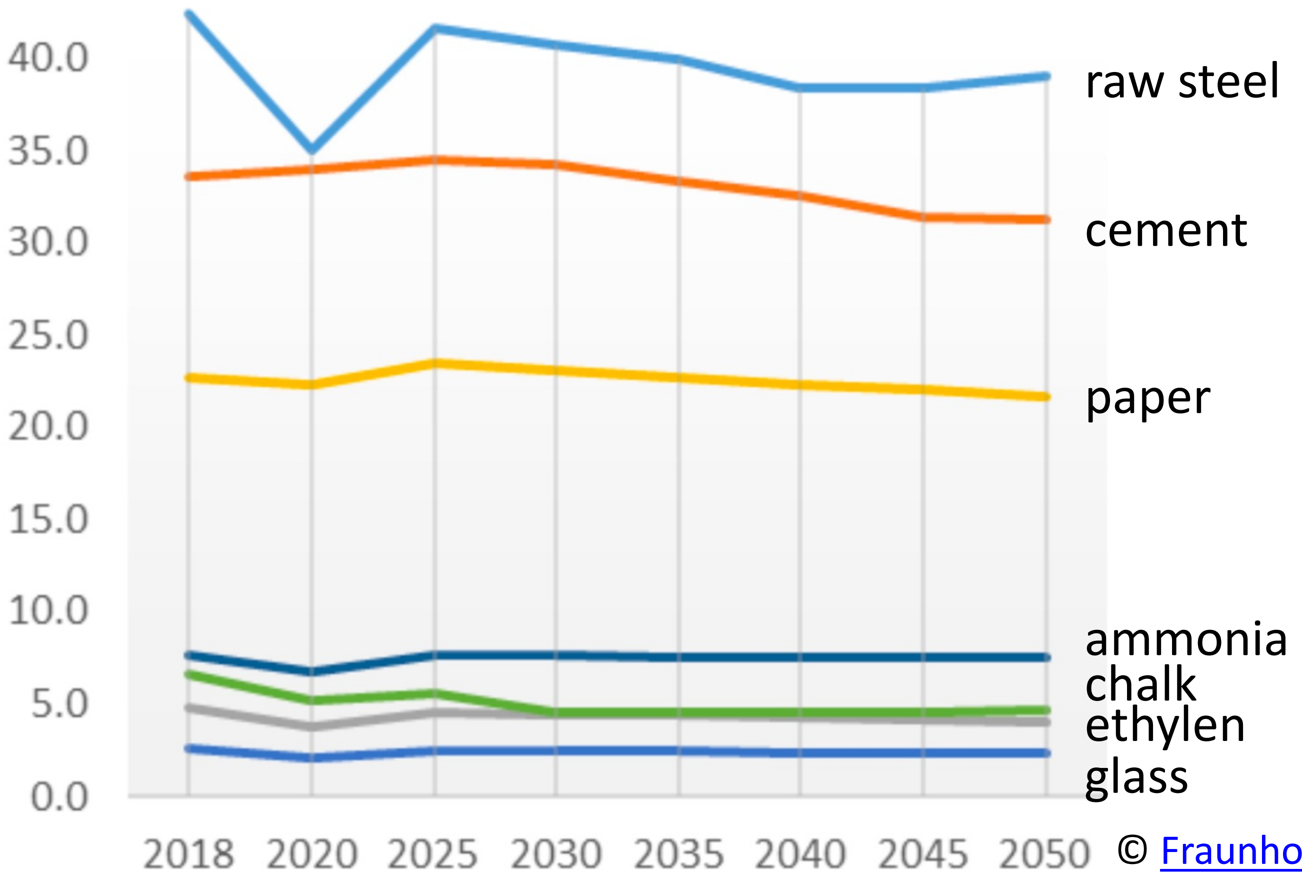
- $ 3,3 bn investment in hydrogen & ammonia
- 1,3 Mt ammonia per year

Australia starts to build a green steel industry

- South Korean steelmaker POSCO invests $ 40 bn in hydrogen & green steel in Australia
- West Australia government-backed programme

Unsustainable assumptions for the German hydrogen strategy: We cannot go on like that!

Production forecast for energy intensive goods in Germany (Megatons)



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We have to reduce the material intensity of our economies

- **Steel:** fully recyclable. Without population growth Europe should essentially work with present stock
- **Glass:** container glass (58% of weight, 21% of turnover in German glass industry) can be massively reduced through re-use
- **Cement:** difficult to decarbonise. Promising: substitution, re-use of structures, avoiding land consumption

Outline

- The global climate challenge
- The future of energy supply is electric: turning away from fire
- PV will be the dominant source of energy
- The geography of cheap energy is dramatically shifting
- Consequences for a European industry policy
- Managing the transformation

European challenges – Managing comparative advantage shifts

- Energy system change will shift patterns of comparative advantages
- Energy-intensive industries, equipment providers and logistics must adapt spatial patterns and volumes
- The workforce must adapt and develop new skills
- Resisting adaptation with subsidies or protectionism comes at a high long-term cost

Energy subsidies for energy-intensive industries are a bottomless pit

Governments must provide:

- **reliable strategic guidance**
- **very selective transformation support**

European challenges –
Managing comparative advantage shifts

We need to discuss & decide strategic priorities:

- dematerialisation of problematic sectors (glass, paper, cement, steel...)
- relocation of energy-intensive industries (raw steel, some chemicals, fertilisers...)
- support of key industries for our economies (renewables, IT, education...)

WE NEED TO WELCOME STRATEGIC CHANGE

DO NOT INVEST IN THE PAST!

Thank you

www.sustainablestrategies.eu

my blog:

https://sustainablestrategies.substack.com