Nuclear Energy in Europe: a technology history perspective

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25nd REFORM Group Meeting, Salzburg
6 October, 2022

www.sustainablestrategies.eu

TECHNOLOGY HISTORY:
NUCLEAR ENERGY IS HOPELESSLY OUTDATED

Nuclear fission: early, seductive fruit of a scientific revolution

1896 Henry Becquerel discovers radiation of Uranium, later called "radioactivity" by Marie and Pierre Curie

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

1902 Ernest Rutherford explains radioactivity by the decay of the uranium atom into smaller elements

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

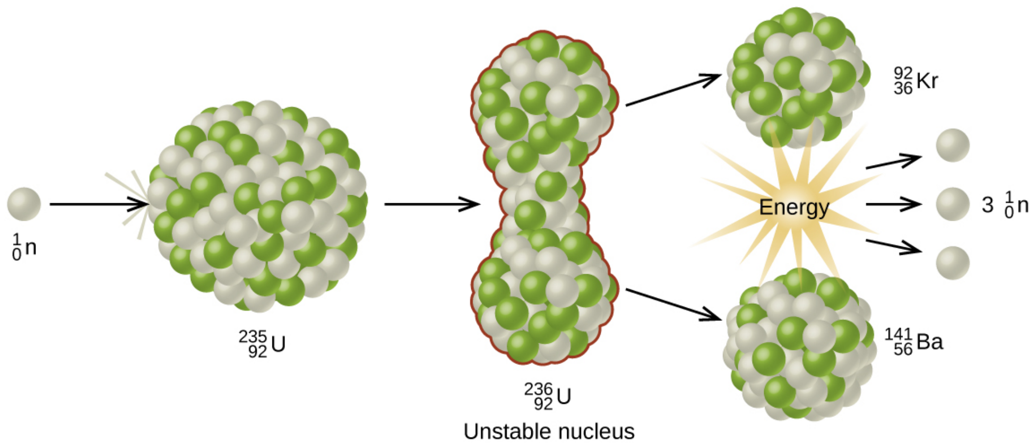
1911 Rutherford's atom model: a small positively charged heavy nucleus is orbited by negatively charged electrons

1926-28 *Heisenberg, Schrödinger and Dirac develop a mathematical formulation of quantum theory*

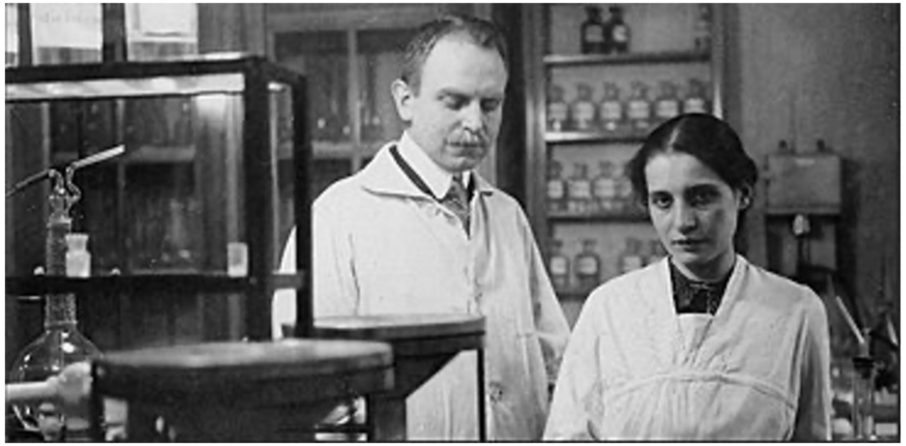
1932 James Chadwick discovers the neutron

1934 Irène and Frédéric Joliot-Curie create new elements by irradiating atoms wit neutrons

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



Nuclear Fission, OpenStax, CC BY 4.0 via Wikimedia Commons



Otto Hahn and Lise Meitner, Wikimedia Commons

Taming the bomb: Inexorably rising costs

1939 Letter to US president Roosevelt by Leo Szillard and Albert Einstein

1942 Start of the Manhattan Project

1942 First self-sustaining chain reaction in nuclear reactor, Chicago

1945 First successful test of nuclear fission bomb

1945 Nuclear bombs on Hiroshima and Nagasaki

1952 **First electricity production with a nuclear reactor EBR-1 (USA)**

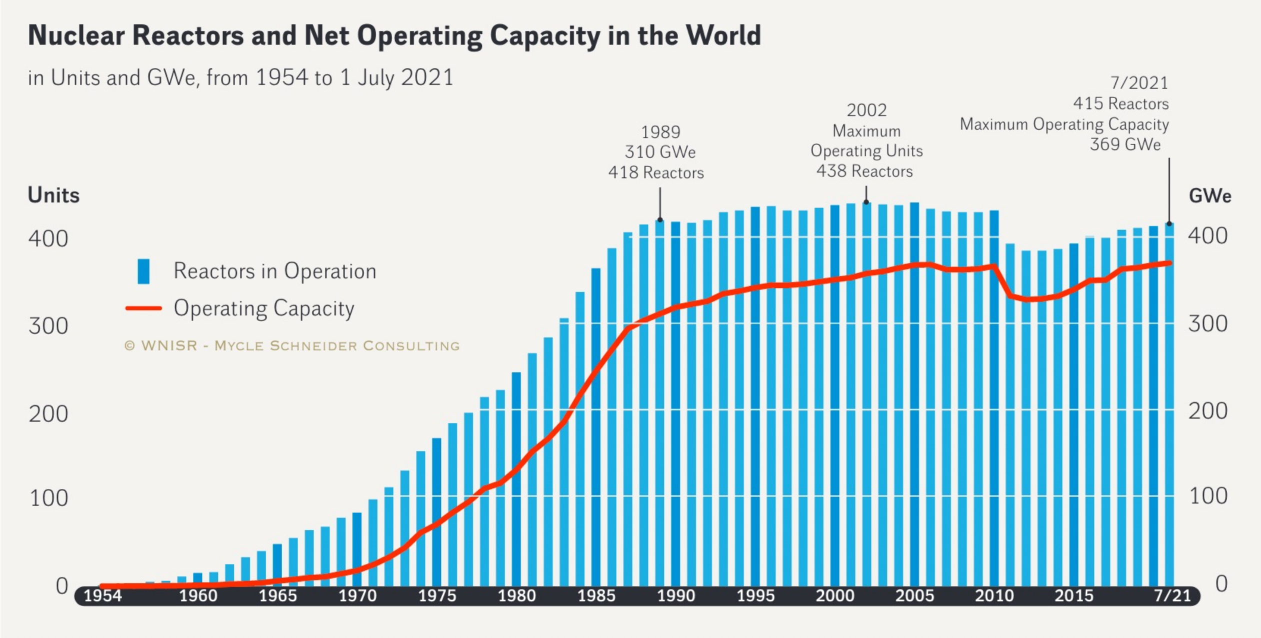
1953 President Eisenhower launches international programme "Atoms for Peace"

1954 First nuclear power plant 5 MW (USSR)

1979 **Three Miles Island reactor accident**

1986 Chernobyl reactor accident

1985 Peak of nuclear reactor grid connections



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<u>**Two key problems**</u>:

- permanent shielding of intensive radioactive radiation on a large scale
- maintaining and containing a potentially explosive chain reaction with unprecedented damage potential

<u>**Efforts for increasing safety led to inexorably rising costs**</u>

Where sensory experience fails: New methods allow the discovery of nano-worlds

1918- Mass spectrometer

1938- Electron microscope

1950- X-Ray microscope

1952- Nuclear magnetic resonance spectrometer

1970- MRI Magnetic Resonance Imaging

1975- MOSFET sensors for chemicals and biochemicals

1981- Image sensors

1961- PET Positron Emission Tomography

Electron microscope, Siemens 1960
Miloš Jurišić , CC BY-SA 3.0

Upheaval in physics 1900-1940 → discovery of nano-worlds where our senses and macro-world experience fail

New methods allow for discoveries of entirely new worlds and opportunities, mainly since 1945

Electronics and digitalisation helped enormously to improve early pilot instruments

Intel 80486DX2 (1992). Matt Britt via Wikimedia Commons

Silicon-based virtual worlds: nanosciences revolutionise information technology

1844 First useful telegraph by Morse

1904 Tubular diode

1946 ENIAC, first fully electronic computer with 19'000 tubes

1947 **Invention of the transistor**

1971 Microprocessor: uniform instruction set, 8'000 transistors

2022 Microprocessor contains 80'000'000'000 transistors

1991 Start of the Internet

2021 4,9 bn internet users

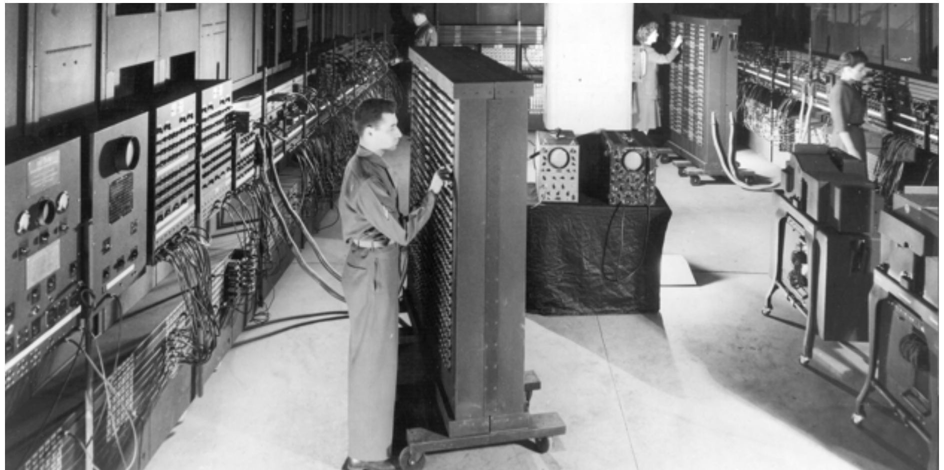
2030 Internet of Things:
* 30 bn connected devices

- Material sciences have triggered a new phase of evolution
- The invention of the transistor was the start for a mind-blowing development of microelectronics

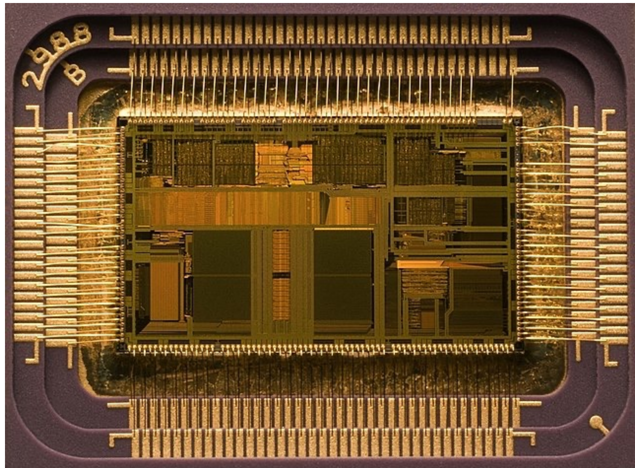
→ Independent sphere of digital information processing – software development has decoupled from hardware

- Digitalisation has deeply transformed our societies
- The information sphere is now starting to deeply transform our handling of matter and energy

ENIAC 1946, US Army photo, Wikimedia Commons



Intel 80486DX2 1992. Wikimedia Commons



Demystifiying the biological information system - No contribution to technical energy supply

1953 Watson & Crick decrypt the basic structure of the DNA

1990 Start of the human genome project

2022 Human genome fully decoded

2013 Single cell sequencing allows for detailed analysis of immune system

2021 mRNA vaccination mitigates Covid-19 pandemic

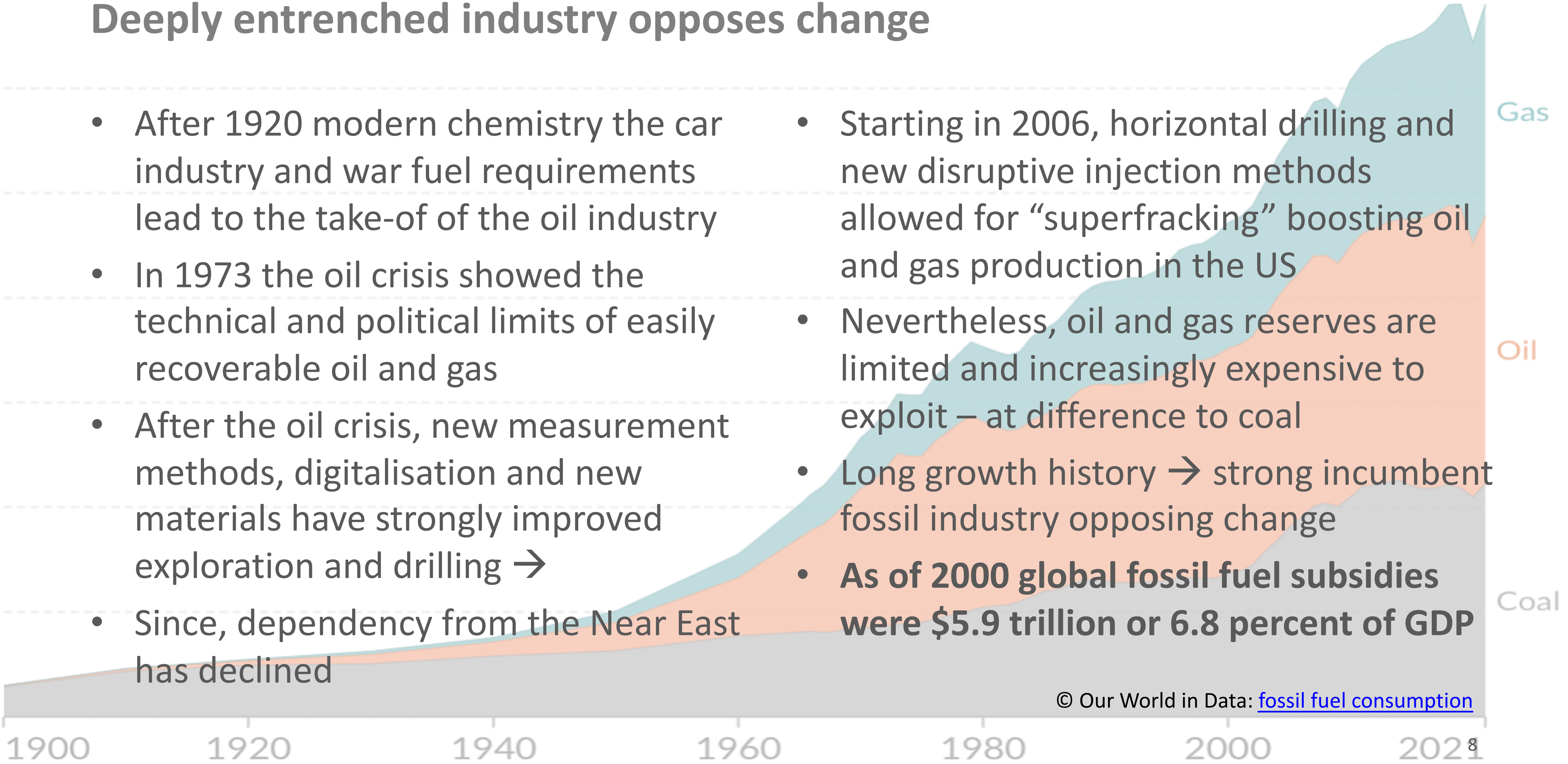
- Nanotechnologies have brought impressive advances in biology and medicine
- Also for high-value organic products – although great caution is necessary
- Sunlight conversion efficiency: photosynthesis plants < 2%, algae in lab < 20%, versus photovoltaics > 24%

→ biomass not adequate for massive technical energy supply

Vehicle Distance From 1 Hectare of Solar Energy of Ethanol from Sugar or Maize

Source: IEEFA: India's ethanol roadmap off course

Fossil fuels
Deeply entrenched industry opposes change



- After 1920 modern chemistry the car industry and war fuel requirements lead to the take-of of the oil industry
- In 1973 the oil crisis showed the technical and political limits of easily recoverable oil and gas
- After the oil crisis, new measurement methods, digitalisation and new materials have strongly improved exploration and drilling →
- Since, dependency from the Near East has declined
- Starting in 2006, horizontal drilling and new disruptive injection methods allowed for “superfracking” boosting oil and gas production in the US
- Nevertheless, oil and gas reserves are limited and increasingly expensive to exploit – at difference to coal
- Long growth history → strong incumbent fossil industry opposing change
- **As of 2000 global fossil fuel subsidies were $5.9 trillion or 6.8 percent of GDP**

© Our World in Data: [fossil fuel consumption]

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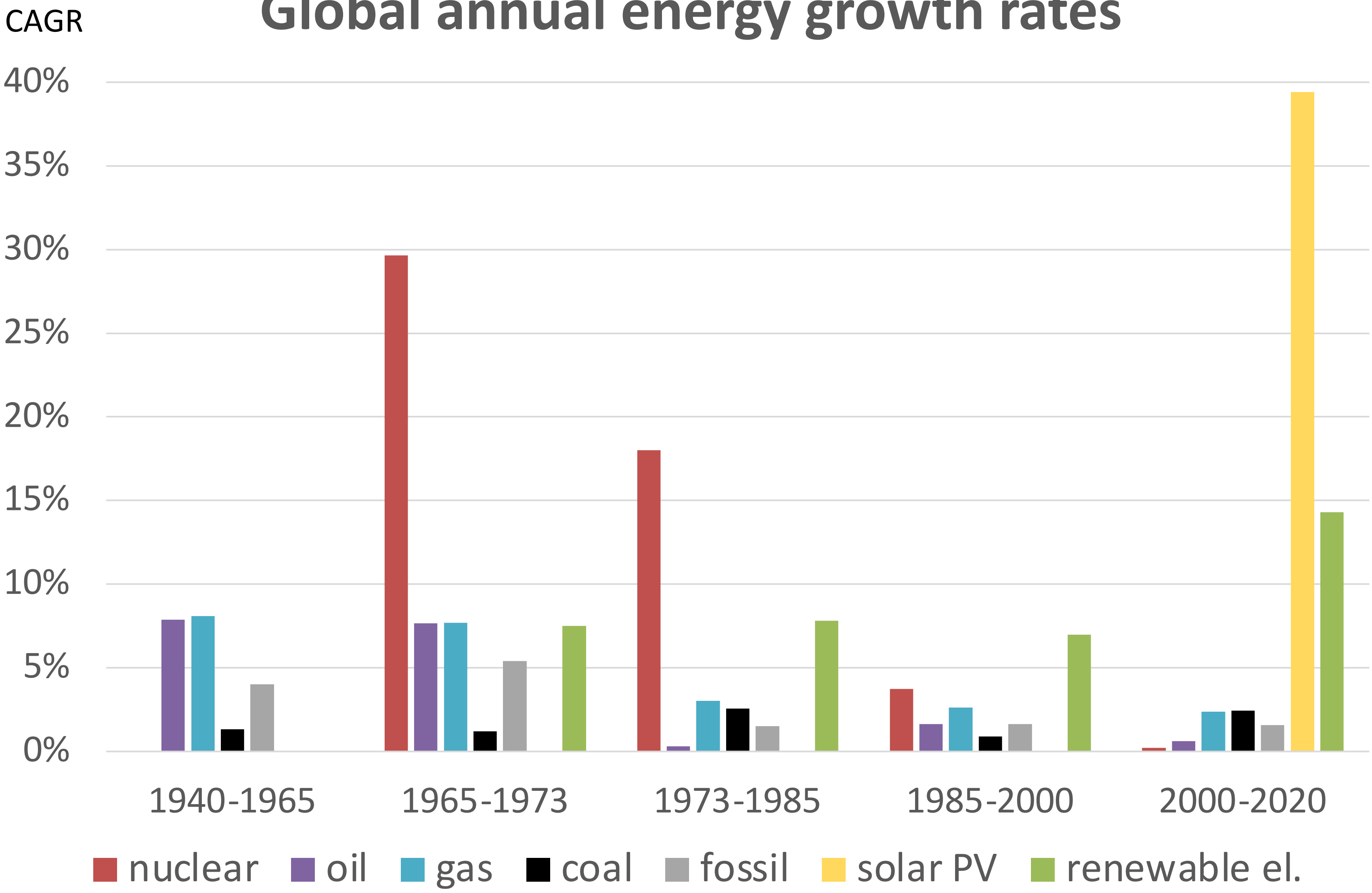
Global annual energy growth rates



- 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

Data: bp energy statistics, Our World in Data

Nanosciences bring cheap electricity from sunlight

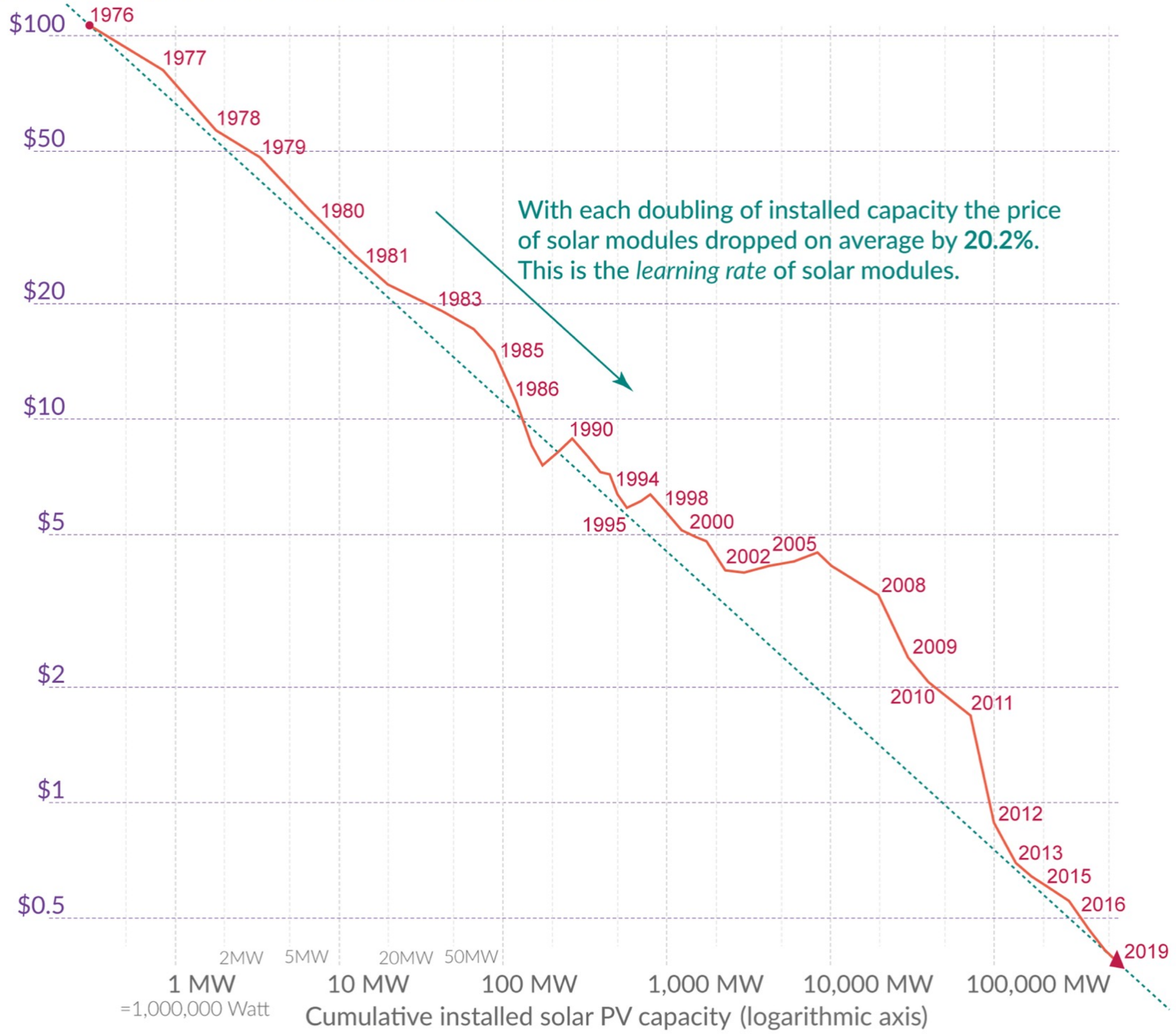
1876	Photoelectric effect on Selenium (Adams)
1900	Light quanta hypothesis (Planck)
1940	Photovoltaic effect in silicon junctions
1950	Explanation of PV mechanism in silicon p/n junction (Shockley)
1954	**PV silicon cell, 6% efficiency**
1958	Space satellites with PV
1973-	Oil companies invest in solar
2006-2017	Chinese global PV market share: 2006: 14,7% → 2017: 71,4%
2009	First perovskite cells, 2021: 25,7% efficiency

- Silicon microelectronics paved the way for photovoltaics
  - Understanding semiconductors
  - High purity silicon crystals in large volumes
  - Coating and doping technologies
- Electricity production at the atomic level allows for high scalability, decentralisation
- Unprecedented cost reductions in energy technology: >95% in 40 years
- Costs increasingly depend on surface-dependent hardware support
  - Efficiency gets more important
  - Integration in existing surfaces gets more important
- **Fluctuating output depending on solar radiation requires flexibilization of the electricity system**

The price of solar modules declined by 99.6% since 1976

Our World in Data

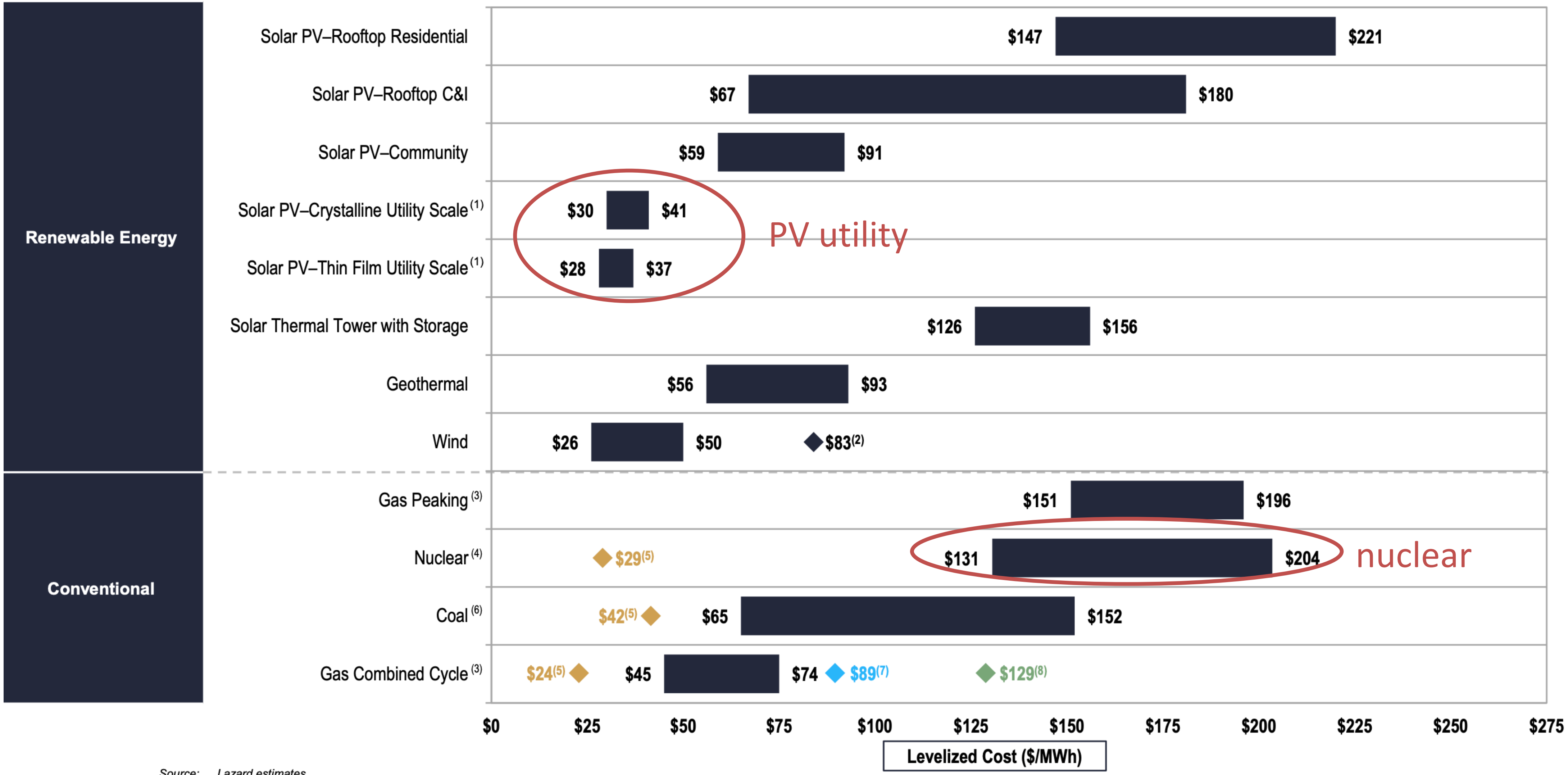
Price per Watt of solar photovoltaics (PV) modules (logarithmic axis)
The prices are adjusted for inflation and presented in 2019 US-$.



Data: Lafond et al. (2017) and IRENA Database; the reported learning rate is an average over several studies reported by de La Tour et al (2013) in Energy. The rate has remained very similar since then.
OurWorldinData.org – Research and data to make progress against the world's largest problems.

Levelized Cost of Energy Comparison—Unsubsidized Analysis

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



Source: Lazard estimates.

Power electronics turns electricity into flexible universal energy

1950 Semiconductor power diode

1956 Silicon controlled rectifier by GE

1959 Power-MOSFET

1976 Commercial power-MOSFET

1982 IGBT

2008 SiC JFET for 1200 V

2011 SiC MOSFET for 1200 V

1960 Laser diode

2021 PE market 27 bn, 2028: 160 bn

- Traditional electric systems: fixed-ratio transformers, electromechanical switching, frequency is constant
- Semiconductor-based power electronics → digitally controlled flexible management of electric parameters
  - Smaller form factor & higher efficiency of equipment
  - Highly efficient motors with variable frequency
  - Higher capacity of distribution and transmission lines
  - No need for large power plants to keep frequency constant
  - Continuous flexible management of all system resources
- Digitalised & power electronics based electricity system gets much more flexible
- Wind turbines, EVs, HVDC transmission rely on it
- Recent: Much higher efficiency with Silicon Carbide (SiC), boost with electromobility
- New material treatment: Laser cutting, 3D printing…

Thyristors in HVDC line pole
©Wikimedia Commons

Nanosciences revolutionise energy storage and transport

1966	PEM (proton exchange membrane) fuel cell
1976	**Principle of reversible intercalation of ions in stable crystal lattices for batteries**
1985	Lithium-ion-battery prototype
1986	Redox-flow battery
2021	Redox-flow nano-particles
2007-	Silicon-nanowire battery
2010-	Aluminium-air batteries with new membranes
1911	Superconductivity discovered
2016	“high-temperature” superconductors

- Batteries dramatically improved through nanosciences
- A wide array of new technologies is emerging since 2000
- **Costs and energy density show similar progress as in PV**
- Boost after passing commercial threshold in mobility & grid
- Promising technologies for electrical aviation and shipping
- Fuel cell improvements enhance hydrogen technologies

Saticoy, 100MW/400MWh battery storage system

© *energy storage news*

Flexibility sources for the electricity system

<table>
<tr><th>Flexibility source</th><th>New technologies</th><th>Regulation</th><th>New developments</th></tr>
<tr><td>Demand side management</td><td>power electronics, communication</td><td>electricity market design</td><td rowspan="4">Small and large consumers produce and store electricity themselves (prosumers). They start to manage consumption, storage and exchange with the grid according to resource availability and market incentives. They integrate electricity, heat and mobility needs in one system.</td></tr>
<tr><td>Flexible generation</td><td>power electronics
materials</td><td>electricity market design</td></tr>
<tr><td>Energy storage</td><td>batteries
hydrogen conversion
power electronics</td><td>energy
market design</td></tr>
<tr><td>Sector coupling</td><td>power electronics,
heat pumps
electric transport</td><td>energy
market design</td></tr>
<tr><td colspan="4">Appropriate market design can encourage development of flexibility resources at each system level</td></tr>
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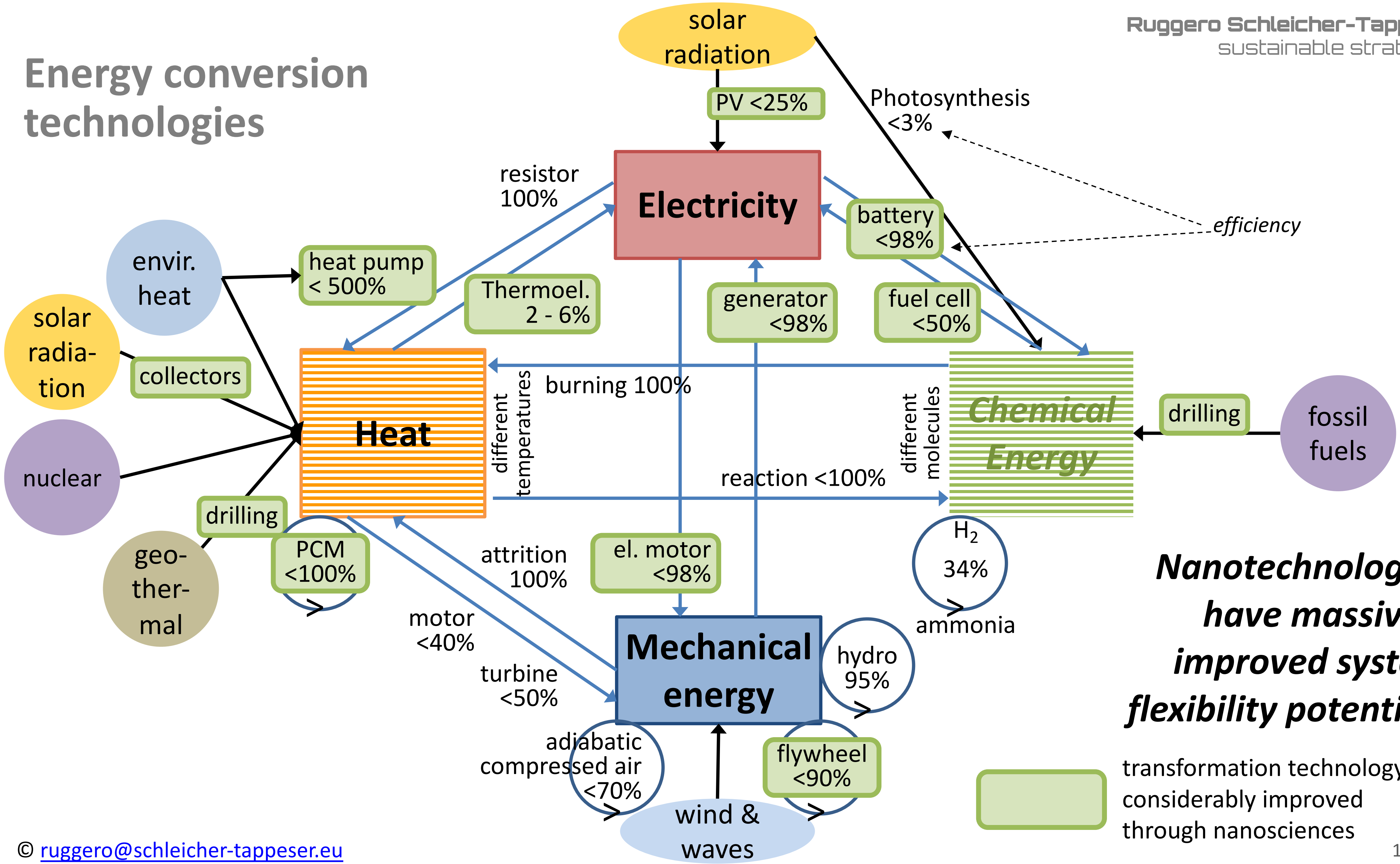
Energy conversion technologies



Nanotechnologies have massively improved system flexibility potentials

transformation technology considerably improved through nanosciences

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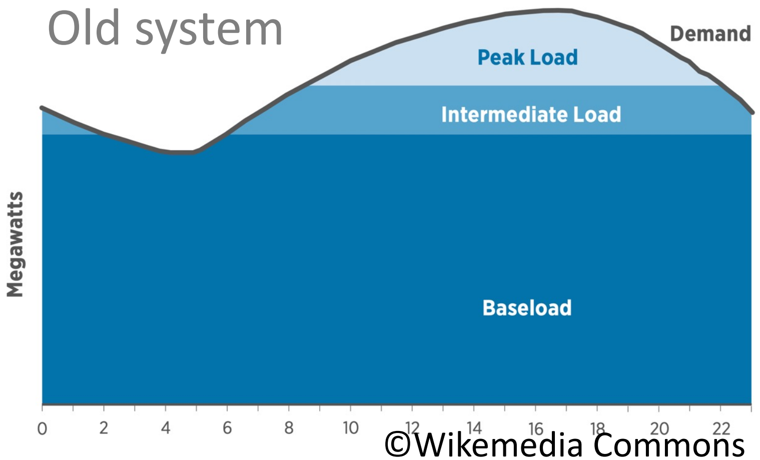
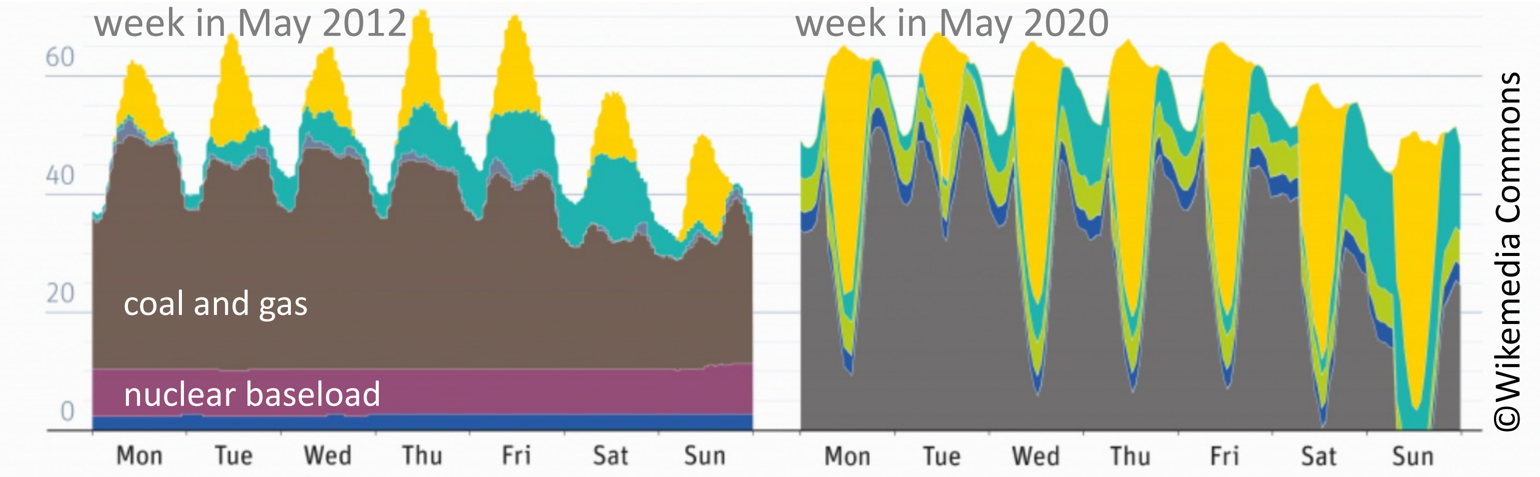
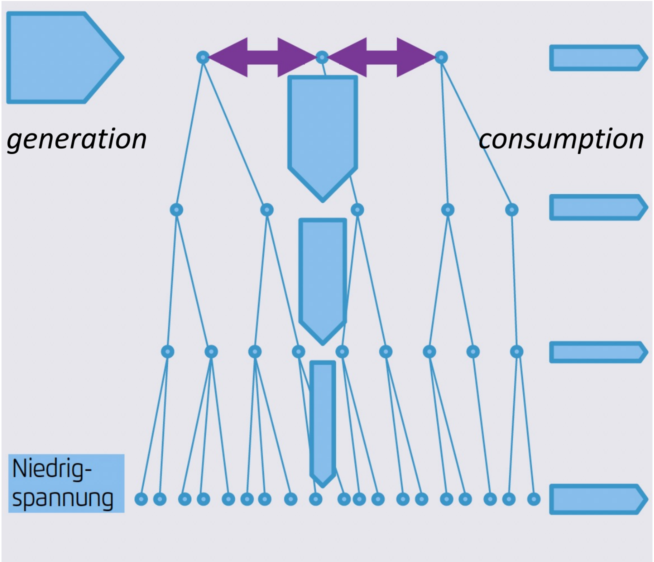
System Transformation



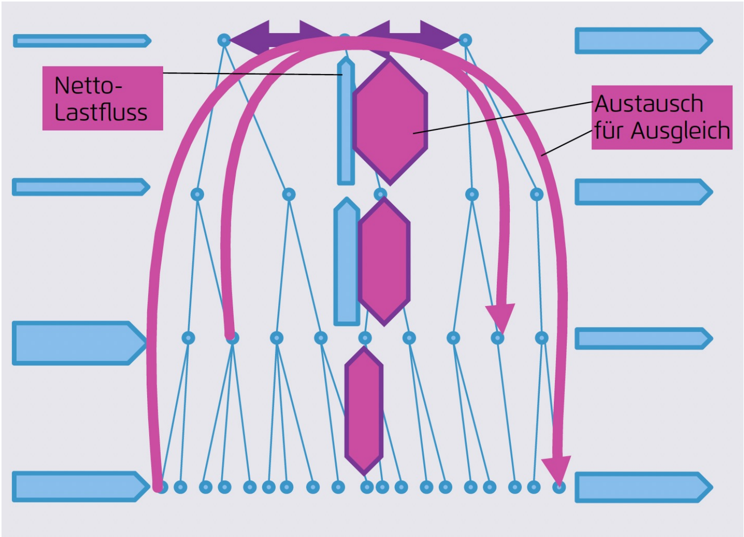
German electricity generation: no use for baseload



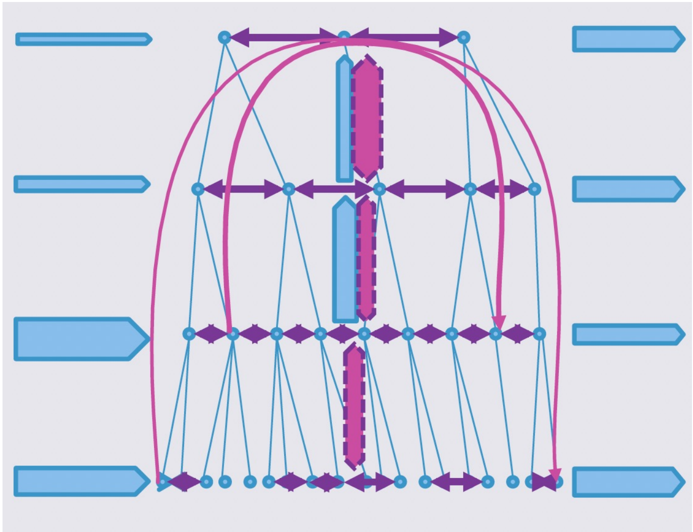
old system
central generation



old system + bidirectional flows
decentral generation



new flexible system
decentral generation



System transformation meets resistance

It requires some effort to understand the new flexible system if you are used to the old one – it has another logic

The change may be comparable to the change from TV to the internet

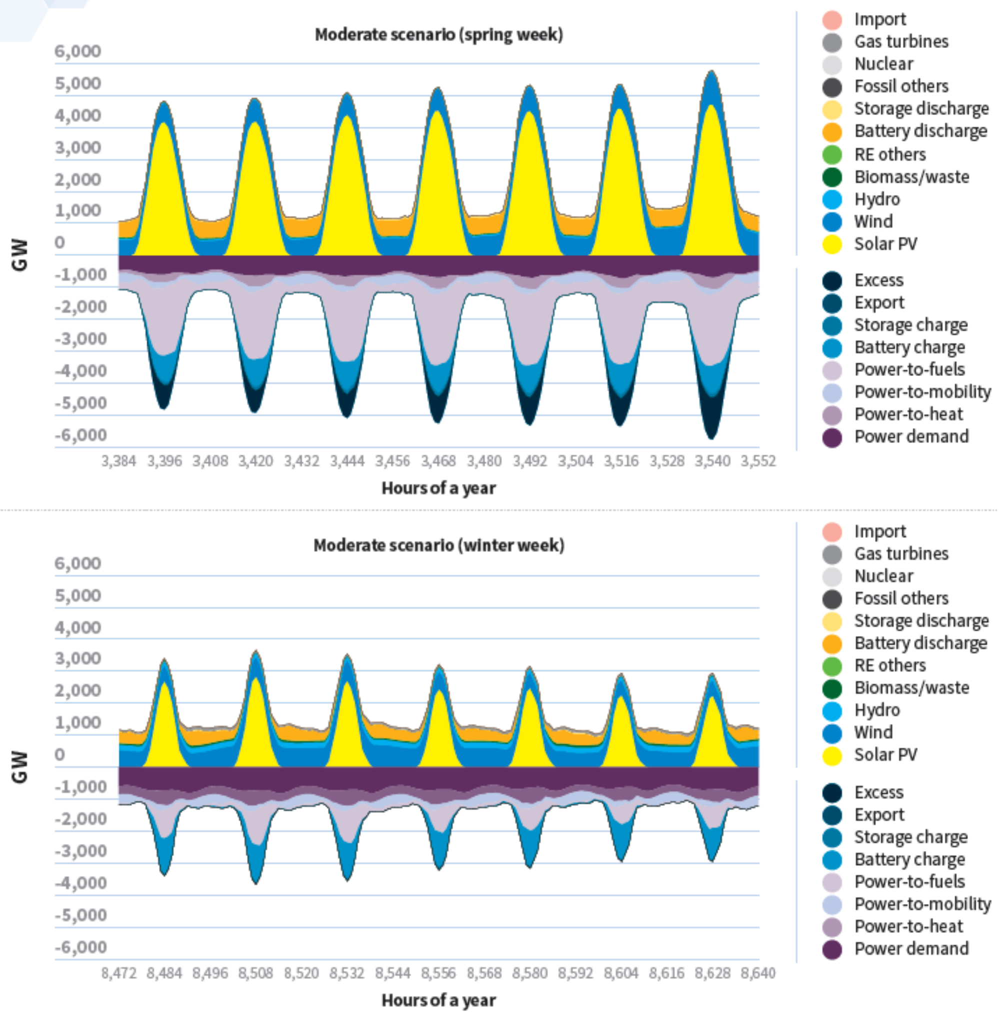
Those countries or regions who insist to stay with the old one will suffer increasing disadvantages

Nuclear power with inflexible baseload hinders flexibilisation and the growth of fluctuating renewable energies

Some incumbent players fear to loose with innovation and foster nostalgia for the ‘good old times’ when all was easy to understand

A fully renewable energy system is possible and cheap

FIGURE 4.8 HOURLY OPERATION OF THE EUROPEAN ENERGY SYSTEM



Key insights:

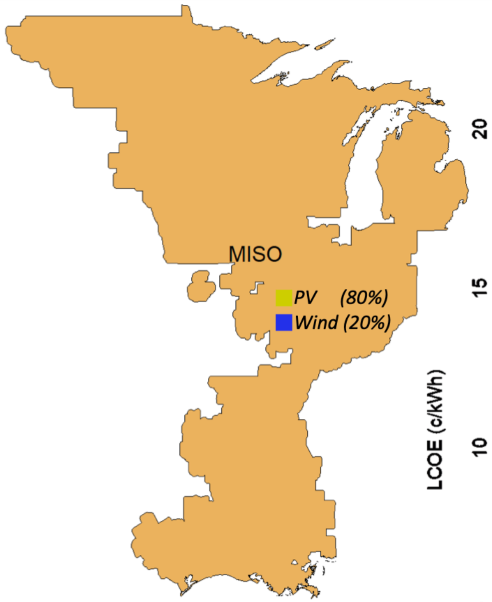
- Week of least renewables supply (winter) and most renewables supply (spring) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the country easily copes with energy demand
- Key balancing component are electrolysers (Power-to-fuels) which convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability
- Massive ramp rates in the energy system have to be managed, as well as forecasting errors require balancing

Detailed modelling by LUT for Europe 2050:

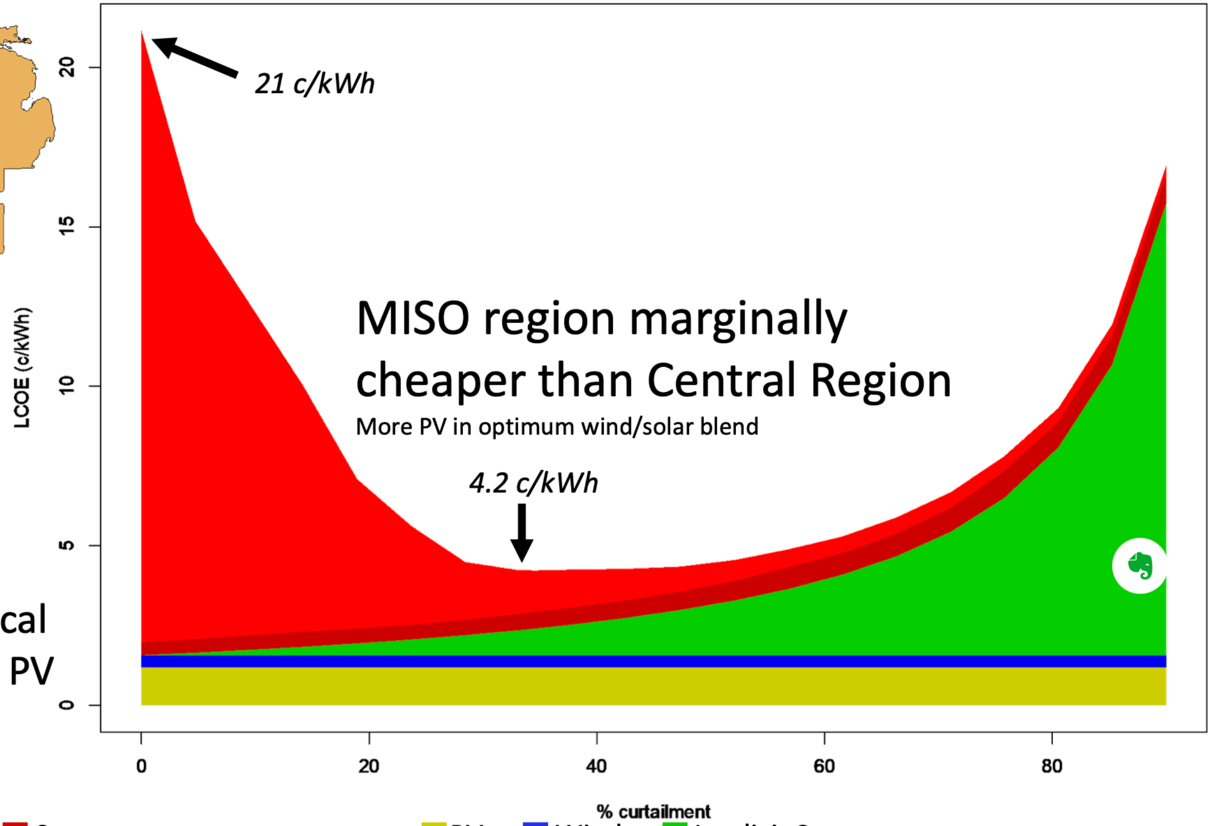
- **A fully renewable energy system for Europe is possible**
- **All sectors included**
- **Costs lower than today: 4,7 ct/kWh**
- **Main source: solar**
- **Curtailment <5%**
- **Hydrogen important for storage**

Link to source

Overbuilding PV + Wind + Batteries sufficient for cheap electricity generation



Consider *MISO*
2050, *high* technological development, Wind + PV



Storage energy component · Storage power component · PV · Wind · Implicit Storage

[Link to source]

Detailed modelling by Clean Power Research for Mid-USA 2050:

- **Fully renewable electricity generation**
- **Costs lower than today: 4,2 c/kWh**
- **57 GW wind + 511 GW PV + 2.7 TWh Storage**
- **Curtailment ca. 33%**
- **No Hydrogen**

Nuclear nostalgia is no viable strategy

Large nuclear reactors have failed to deliver cheap energy

- newest generation has slightly improved safety but not the costs
- average age of plants is over 30 years
- fast breeder and high temperature reactors have been given up
- nuclear power plans are strongly linked to nuclear weapon ambitions
- Only Iran, China, Pakistan , India and Russia increased nuclear power output (> 2%) in the last decade

The nuclear community now propagates small modular reactors (SMRs)

- They hope for
  - Simpler, safer design
  - Cost reduction through serial production
  - Advanced concepts for more efficient fuel use or higher operating temperatures
  - Local heat use
- No prototypes yet. One rather traditional concept approved by US-NRC. Difficulties for assessing safety of new concepts
- 10 to 20 years away
- Serious doubts on safety, cost advantages

Doubts on SMR safety, cost and systemic advantages

Safety issues

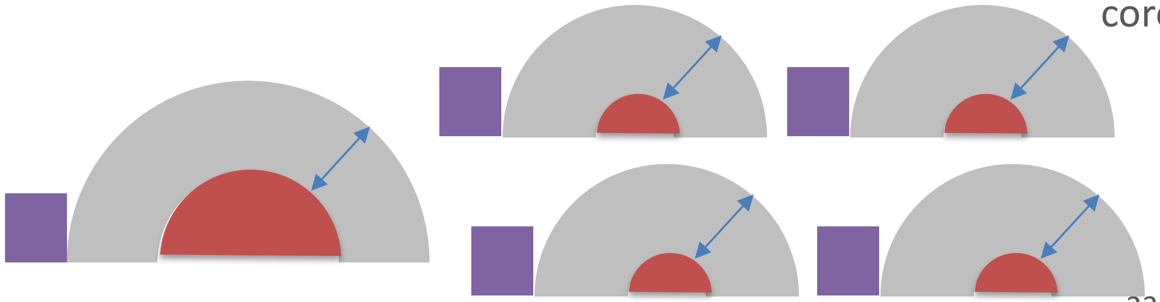
- Possibly increased inherent safety countervailed by new risks
- Multitude of plants and transports more susceptible to external threats
- Missing safety criteria for new concepts with molten metals, reprocessing, liquid fuel, high temperatures, new dynamics
- Reduced number of safety barriers

Cost issues

- Serial production cost effects require high numbers (>3000?)
- New equipment production plants needed
- Many interfaces between different industries
- Safety and radiation protection overhead share grows for smaller units
- [assuming costs related to: unit 20%, surface 35%, volume 45% → downscaling to 1/10 → 320% costs per power unit, not counting transport]

Basic issues of nuclear power remain:

- **Shielding of radioactive radiation**
- **Potentially explosive chain reaction**



core =1/10

Nuclear is definitely an outdated technology

Too costly

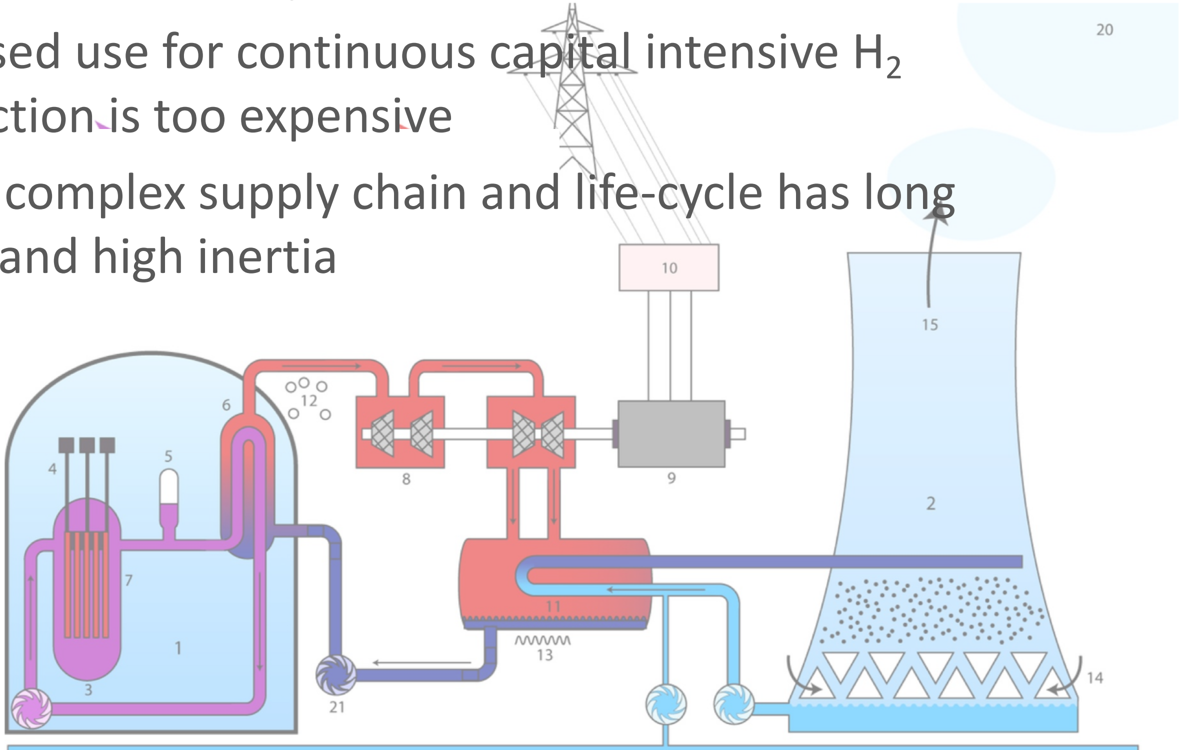
- Nuclear, new large : 13 – 20 ct/kWh →
- Low chance of SMRs being cheaper ↗
- Old nuclear operation : 2,9 ct/kWh ↗
- PV power plants : 1 – 4 ct/kWh ↘
- Battery : 150 €/kWh capacity, assume 7k cycles → 2,1 ct/kWh ↓
- PV + Battery & assumptions, <8ct/kWh

Too slow

- Nuclear, new large: 10 y to build, 20 y to decommission
- SMRs: technological readiness >10y ↗, supply chain >5y ↗, plants >3y ↑
- PV power : supply chain expansion 1–5y, plant construction 0,5 y ↘

Lock-in for inflexible system

- Nuclear power plants are not dispatchable – unsteady operation causes material stress
- Nuclear delays system transformation – baseload contradicts flexibility needed for renewables
- Proposed use for continuous capital intensive H_2 production is too expensive
- Highly complex supply chain and life-cycle has long cycles and high inertia



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Nuclear energy harvesting needs huge ancillary systems for fuel provision, safety, radiation protection, low-efficiency energy conversions (heat → mechanical energy → electricity) and waste disposal

PV & batteries use nano-level high-efficiency energy conversions (radiation → electricity / electricity ←→ chemical) without risks and huge overhead

Wind requires huge mechanical structures for converting wind into rotational mechanical energy – risks, supply chain complexity and required times are reasonable

THE CASE OF FRANCE: REACTORS & BOMBS
NATIONAL MYTH BEATS ECONOMIC RATIONALITY

European energy policy is blocked by a fundamental dissent France/Germany on nuclear power

„Sans nucléaire civil, pas de nucléaire militaire, sans nucléaire militaire, pas de nucléaire civil“

"Without civil nuclear power, no military nuclear power, without military nuclear power, no civil nuclear power”

President Macron in his programmatic speech on the future of nuclear power on 8 December 2020

- F has the highest share of nuclear energy: 70% of electricity, 56 reactors, 61,4 GW
- EDF: expected net debt end 2022: €65 bn, will be nationalised this year
- 32 out of 56 reactors out of service
- Macron announced in 2022:
  - Programme for SMRs
  - 6 new EPR2 reactors ready in 2035 + 8 later
  - Lifetime extension of reactors to 50 years
  - Efforts for exporting nuclear technology
- Dissent between France and Germany blocks European energy policy

How can we overcome this divide?

Beginnings of French nuclear energy and bomb – core elements of national independence and pride

1945 De Gaulle establishes “Commissariat à l’Energie Atomique” **CEA**

Nobel Prize & communist resistance member Joliot-Curie + former armament minister Dautry first directors

No exchange with US-AEC

1948 First French reactor successful

1950 Joliot-Curie expelled after signing Moscow-led disarmament petition

1954 CEA starts to prepare nuclear bomb

1958 De Gaulle in power again, makes nuclear armament public

1960 First successful French bomb test, US, UK had denied collaboration

1966 France retires from NATO, headquarter moves to Brussels

1946 Creation of national state monopole utility Electricité de France **EDF**, a symbol of left industry policy and union stronghold

1954- CEA increasingly nationalistic, dissimulates armament by promoting nuclear power programme and cooperation with EDF, similar to Eisenhower’s ”Atoms for peace” (1953)

CEA and EDF differ on technical and industrial strategy but agree on high priority for a French national nuclear technology

Development of an own graphite reactor

1957 Establishment of EURATOM, divergent national interests, develops own ORGEL reactor line, later abandoned

1968- France gives up graphite reactor, switches to a “nationalised” PWR based on US license

Against all odds France bets on nuclear
Europe will have to pay – one way or the other

1958 Establishment of reprocessing plant in Marcoule for extracting bomb-grade plutonium out of spent reactor fuel

1961 Decision for a second military reprocessing plant in La Hague, repurposed for civilian use in 1969

1973 Oil crisis, decision to massively expand nuclear power for getting more independent from oil

2001 CEA's industrial daughters merge under the roof of AREVA. Massive losses → sale of grid technology branch

2014 € 4bn losses of AREVA → plans for large F-D-CH PV panel factory abandoned, stepwise decomposition of AREVA

2022 France succeeds to include nuclear in EU taxonomy for facilitating the financing of nuclear projects

Today CEA is still the leading French applied research organisation with 16'000 staff: nuclear energy & armament, alternative energies, electronics, materials

FACING AN INCONVENIENT TRUTH

- **The nuclear adventure of France may lead to huge costs and competitive disadvantages for Europe**
- **France will not give up its nuclear armament (bombs, ships)**

→ ***The only way to give up nuclear electricity ambitions and agree on a renewable path for Europe is to clearly separate civilian and military use of nuclear power***

→ ***This may require additional European funding for the French bomb***

ARE WE READY TO AGREE ON THAT?