

Nuclear Energy in Europe: a technology history perspective

Ruggero Schleicher-Tappeser

guest lecture

TUM School of Social Sciences and Technology

Technical University of Munich

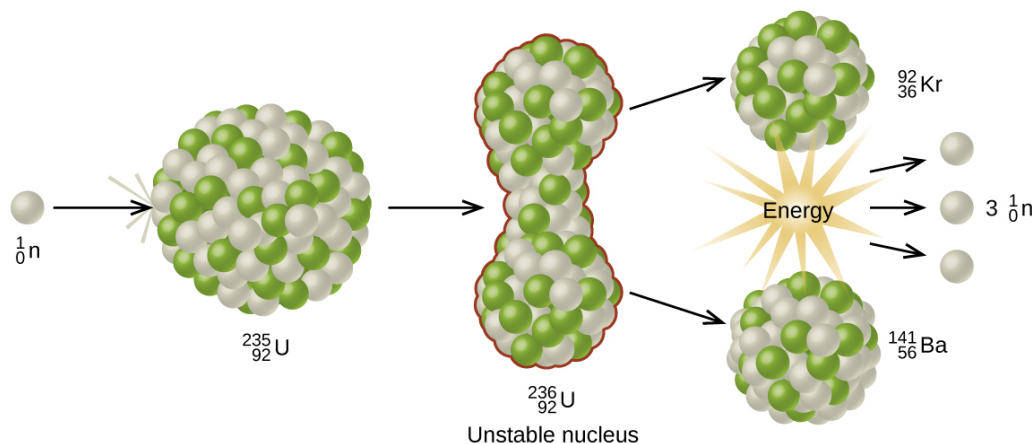
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**TECHNOLOGY HISTORY:
NUCLEAR ENERGY IS HOPELESSLY OUTDATED**

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



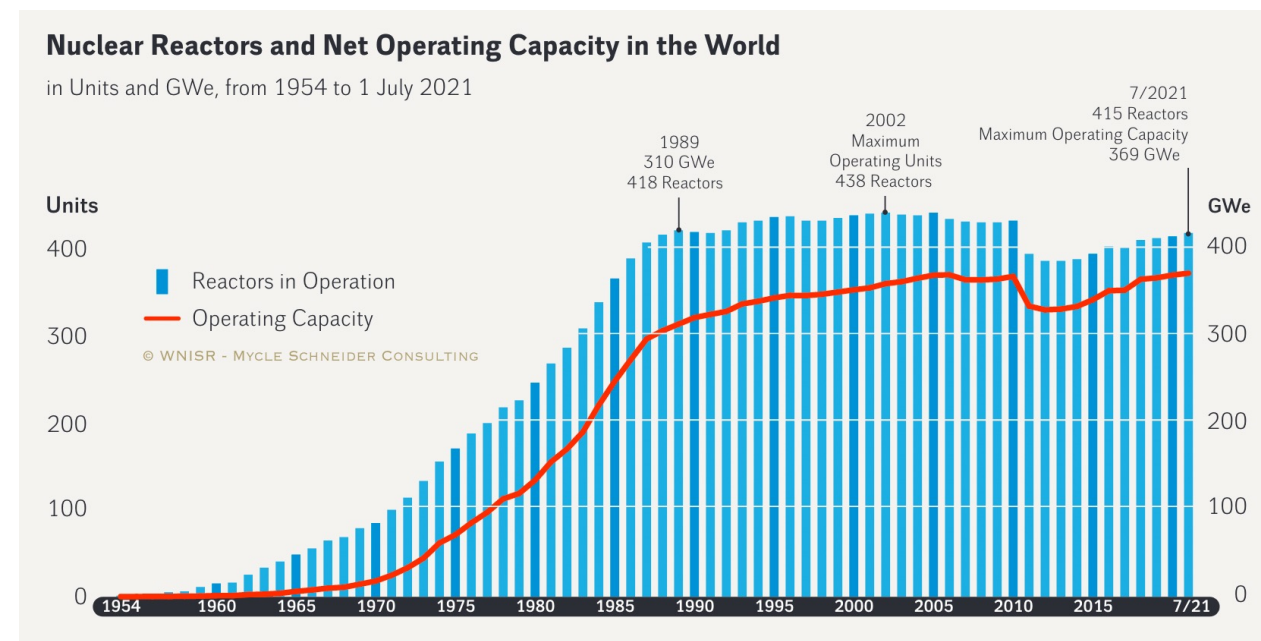
Nuclear Fission, OpenStax, [CC BY 4.0](#) via Wikimedia Commons



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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Two key problems:

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

Efforts for increasing safety led to inexorably rising costs

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](https://creativecommons.org/licenses/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

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

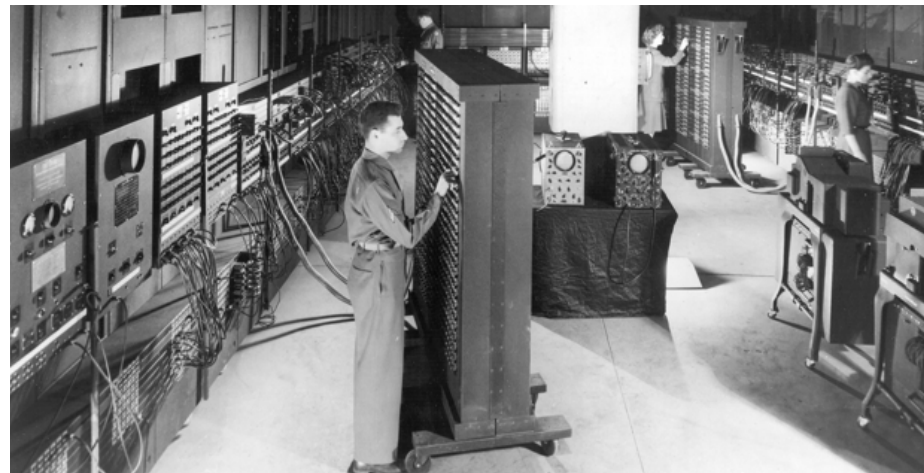
1991 Start of the Internet

2021 4,9 bn internet users

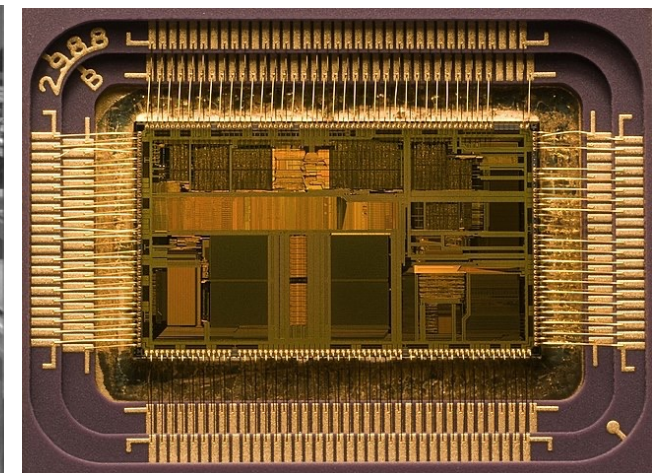
2030 Internet of Things:
* 30 bn connected devices

- 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



Demystifying 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

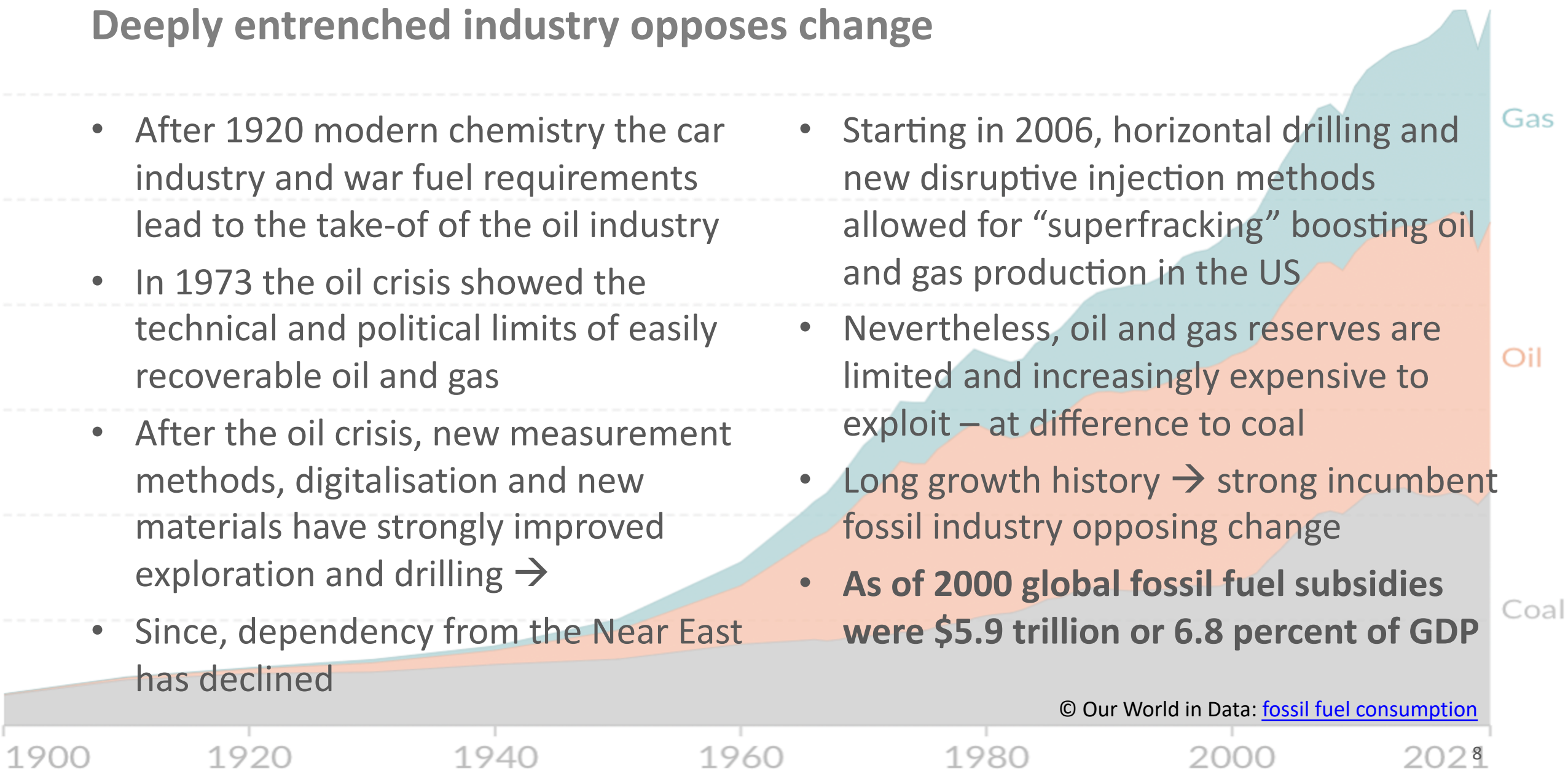


Source: IEEFA: [India's ethanol roadmap off course](#)

Fossil fuels

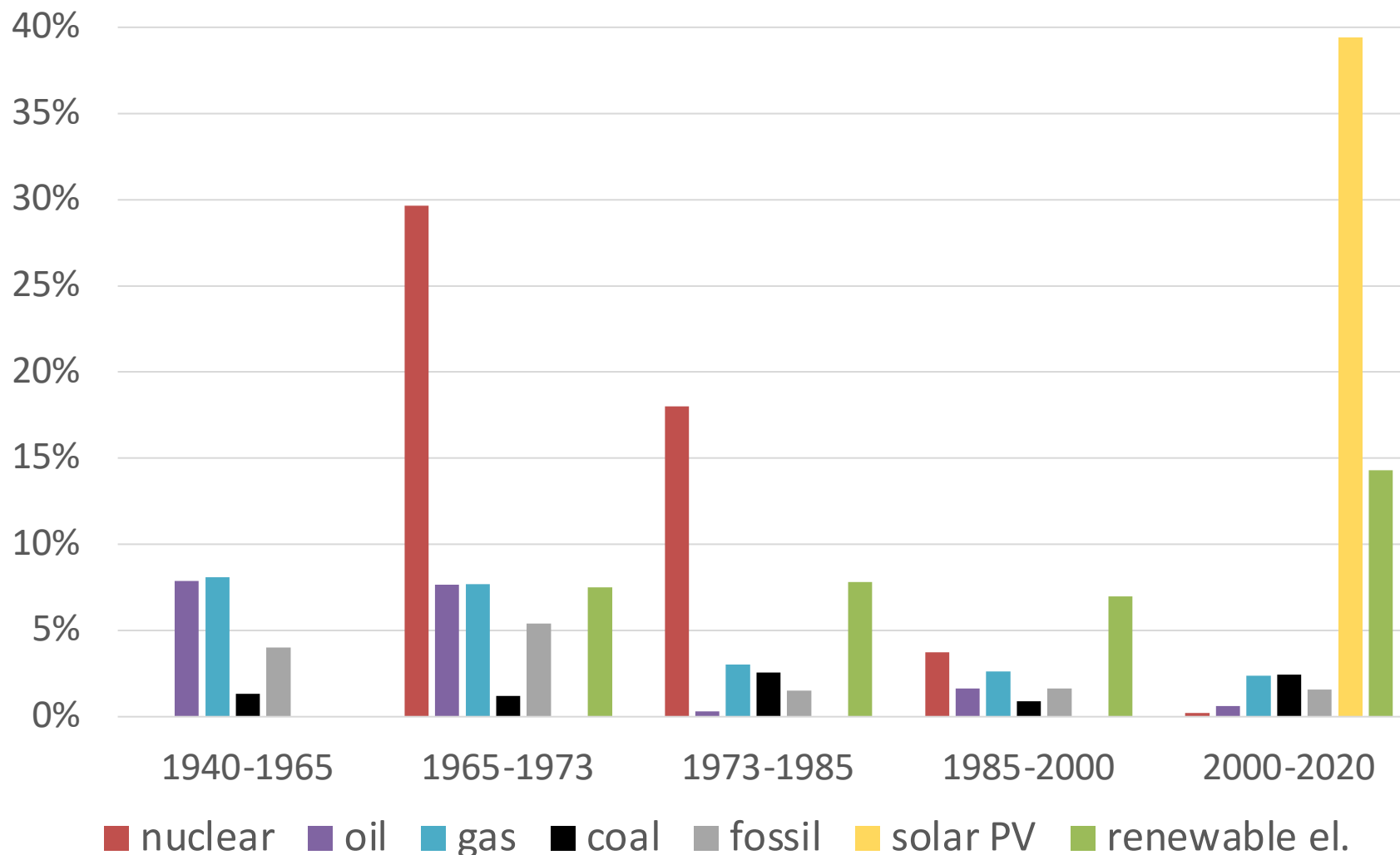
Deeply entrenched industry opposes change

- After 1920 modern chemistry the car industry and war fuel requirements lead to the take-off 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**



Global annual energy growth rates

CAGR



- 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

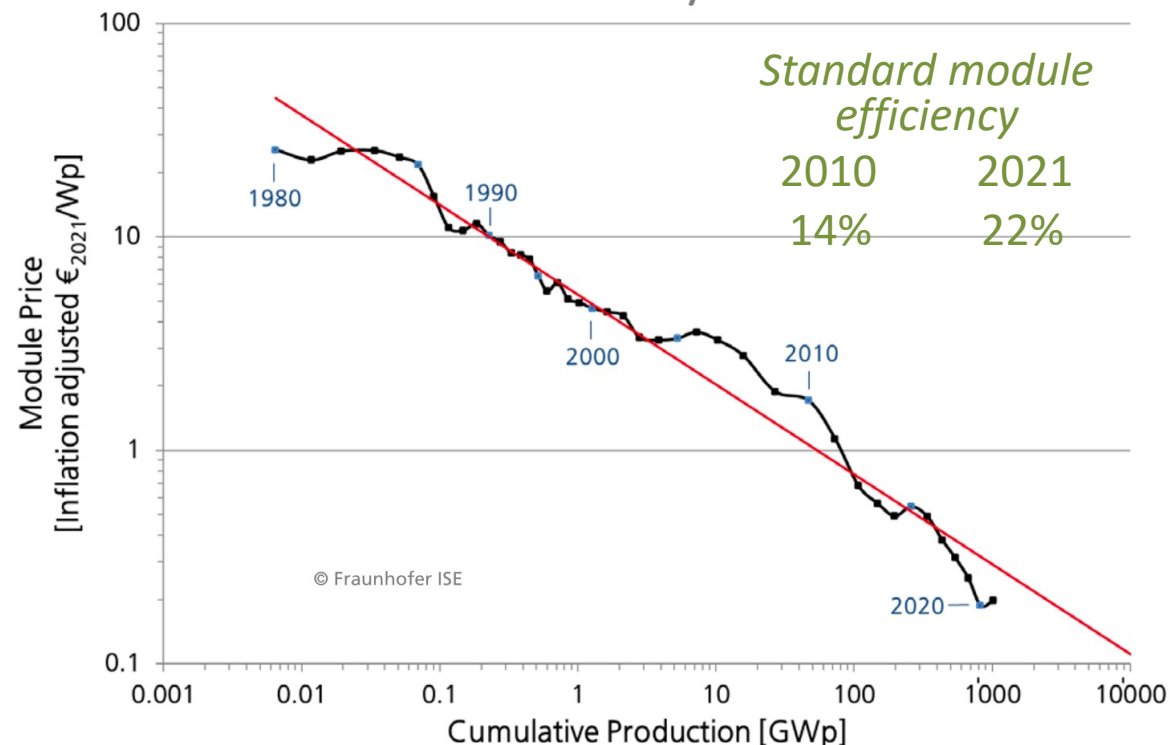
Nanosciences bring cheap electricity from sunlight

1876 Photoelectric effect on Selenium
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- China conquers global PV markets:
-17 2006: 15% → 2017: 71%
2012 EU governments crash their PV market
2019 Top cell efficiency 47%
2021 Perovskite cells 25% 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 → scalability
- Unprecedented cost reductions in energy technology: >99% 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**

A disruptive and superior technology

Over 99% cost reduction in 40 years



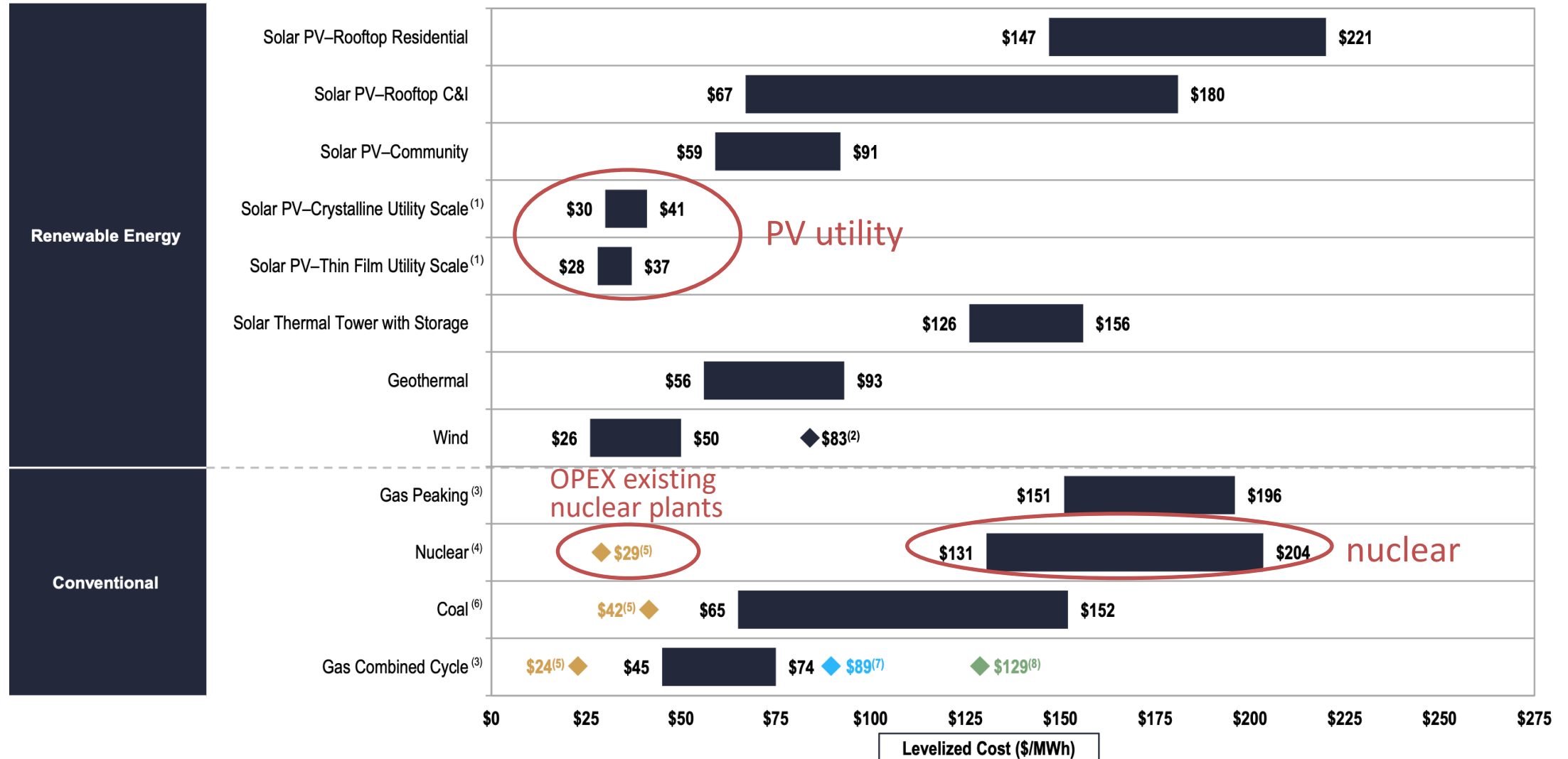
PHOTOVOLTAIC DEVICES

1. **Are extremely reliable:** No moving parts, no fuel, very low risks, essentially no maintenance during 30 years
2. **Can be mass-produced:** Classical economies of scale and learning curves
3. **Innovate rapidly at nano-scale:** high-potential core process, simple ancillary structures
4. **Are extremely scalable, up and down:** Energy transformation occurs at nano-level
5. **Can be deployed rapidly:** Innovation cycles ten times shorter than conventional power

PV is a surface-related nanotechnology outpacing other renewable energies. Rapid further progress in efficiency, material needs and suitable surfaces is guaranteed.

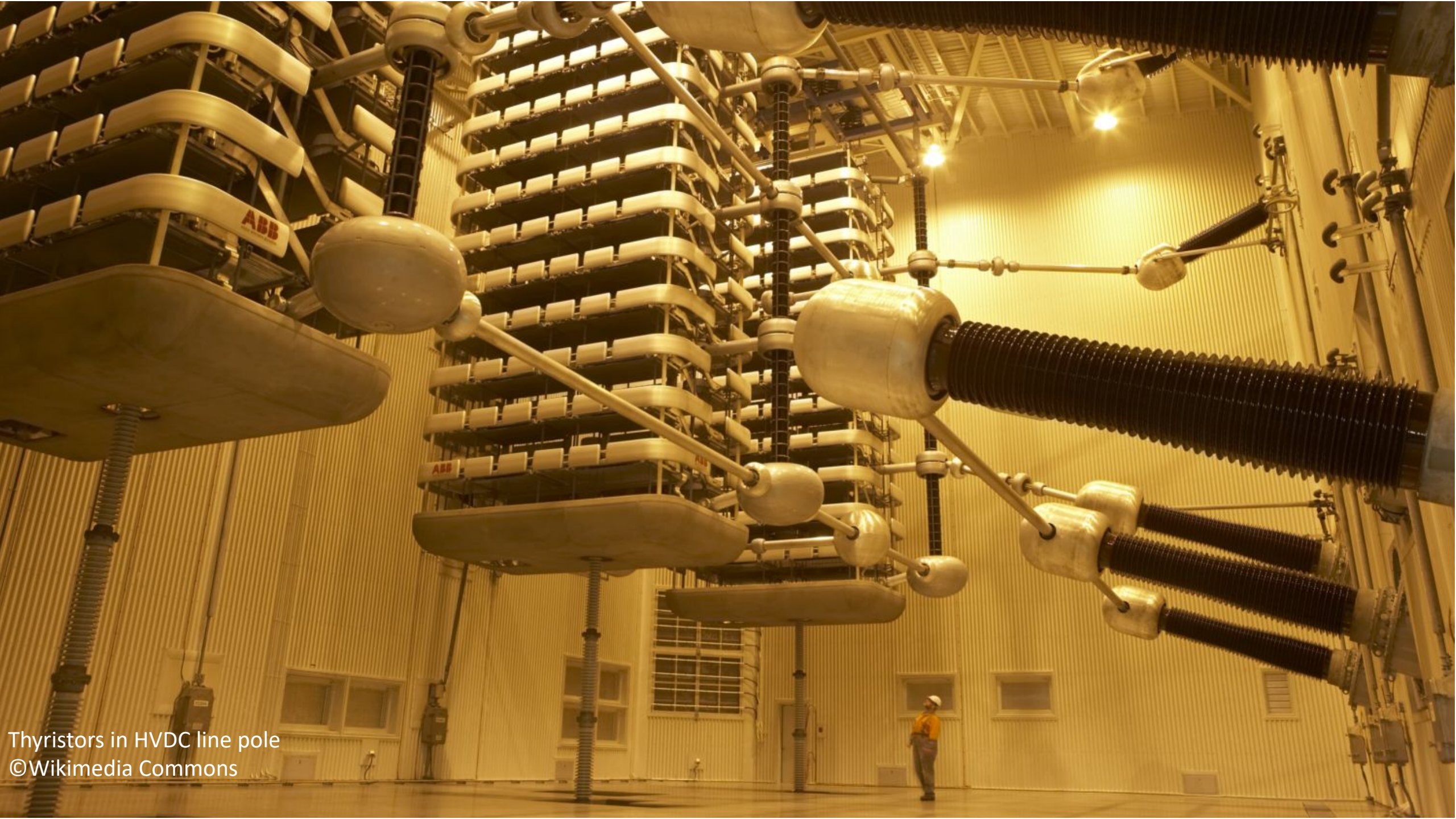
Levelized Cost of Energy Comparison—Unsubsidized Analysis

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



Power electronics turns electricity into flexible universal energy

- 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...
- | | |
|-------------|------------------------------------|
| 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 |



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

Flexibility source	New technologies	Regulation	New developments
Demand side management	power electronics, communication	electricity market design	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.
Flexible generation	power electronics materials	electricity market design	
Energy storage	batteries hydrogen conversion power electronics	energy market design	
Sector coupling	power electronics, heat pumps electric transport	energy market design	
Appropriate market design can encourage development of flexibility resources at each system level			

Useful energy we need

Elmag. Radiation /
Light

*illumination,
communication
photochemistry*

Electricity

*communication,
computing,
controlling*

different
temperatures

Heat

*heating,
transforming
materials*

different
molecules

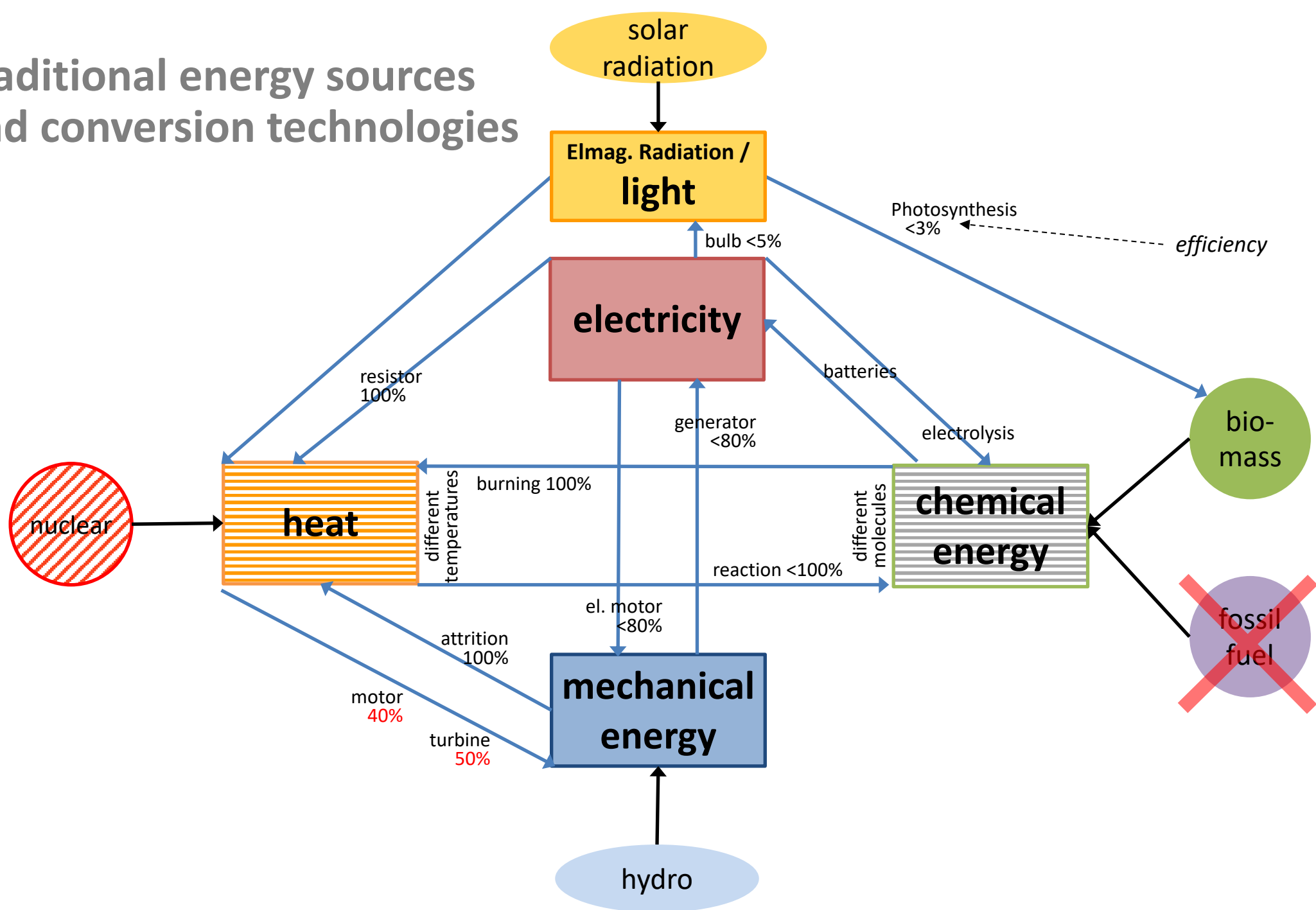
**Chemical
energy**

*(food),
(chemical processes)*

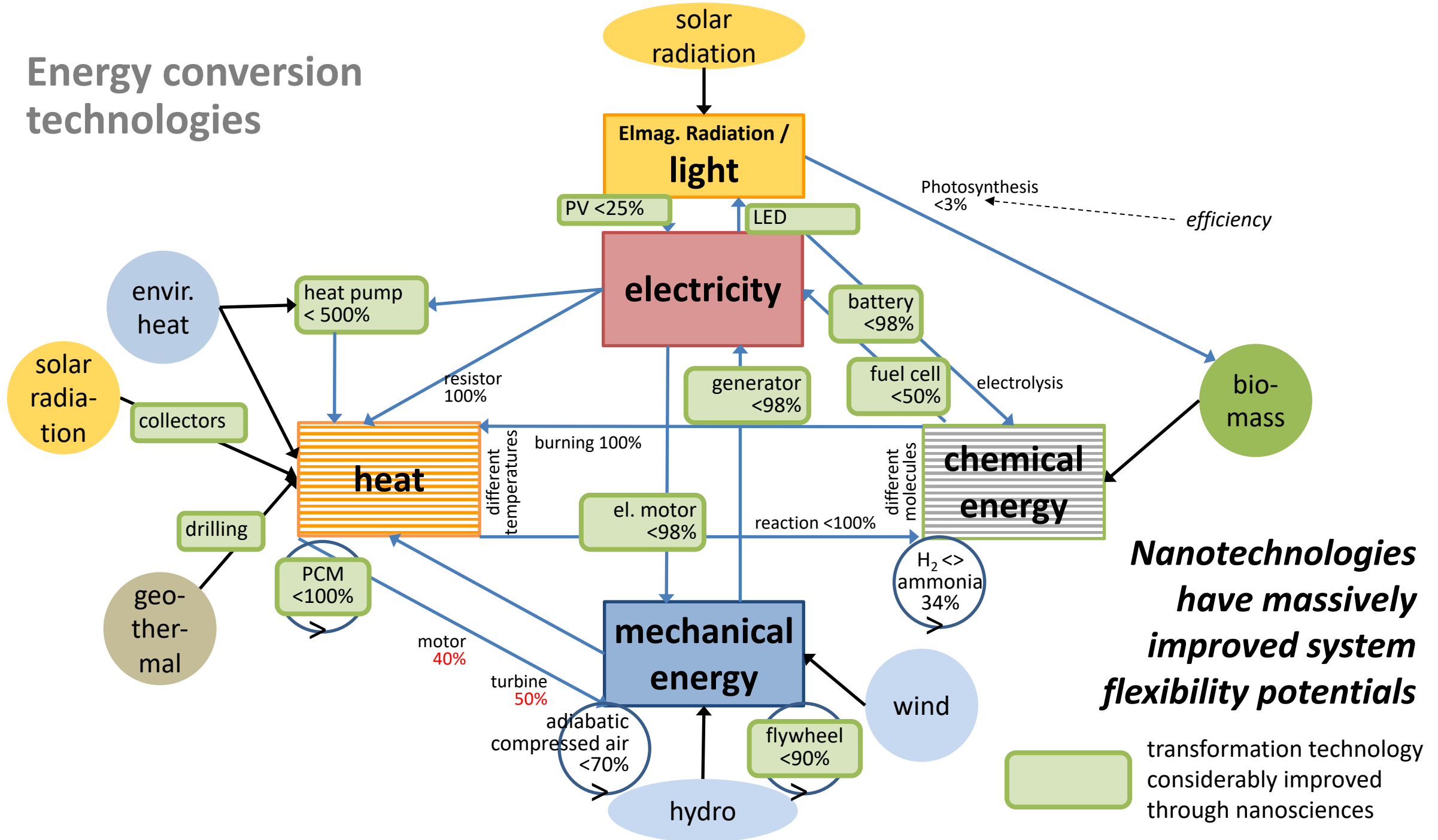
**Mechanical
energy**

*transport,
transforming
materials*

Traditional energy sources and conversion technologies

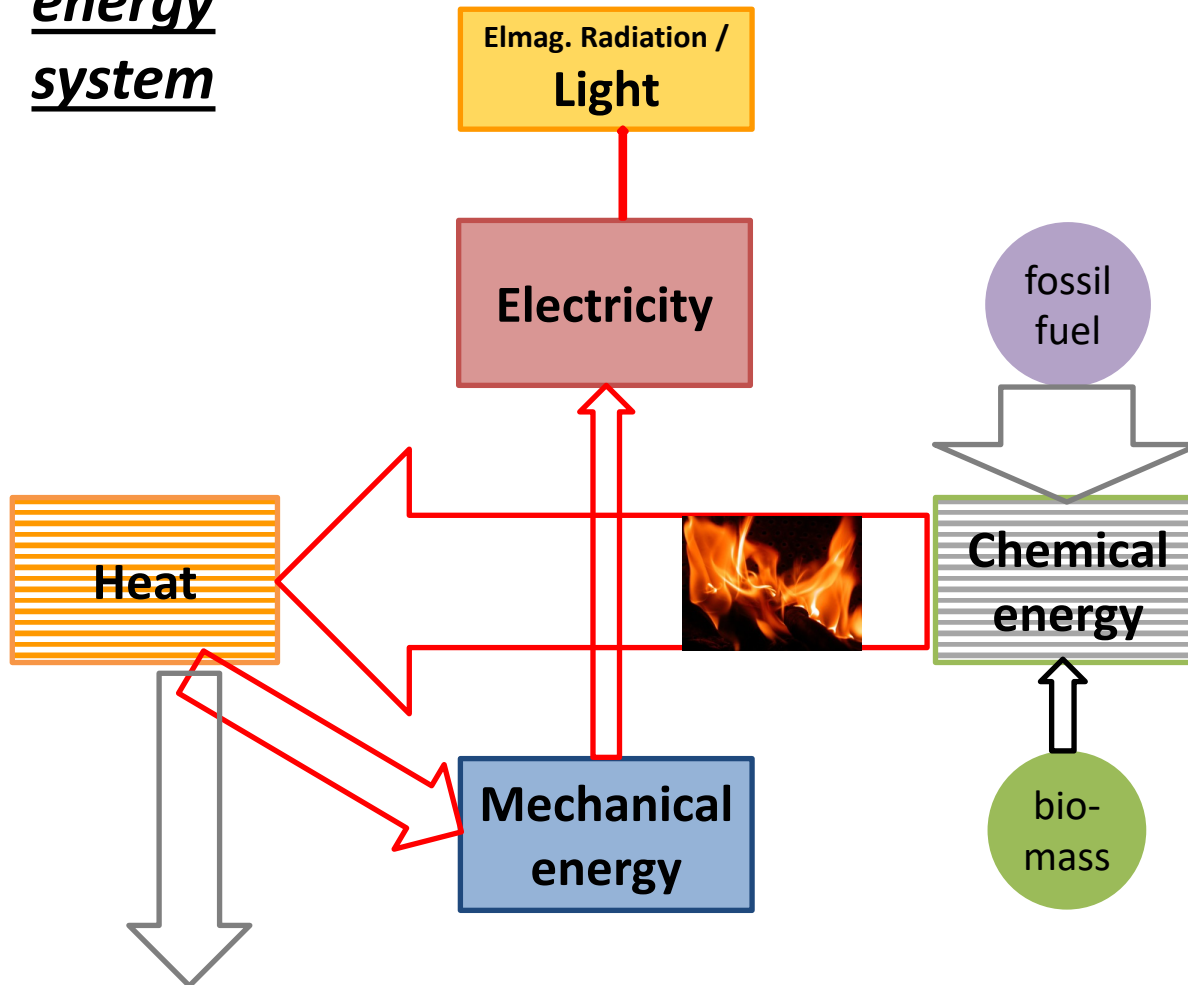


Energy conversion technologies

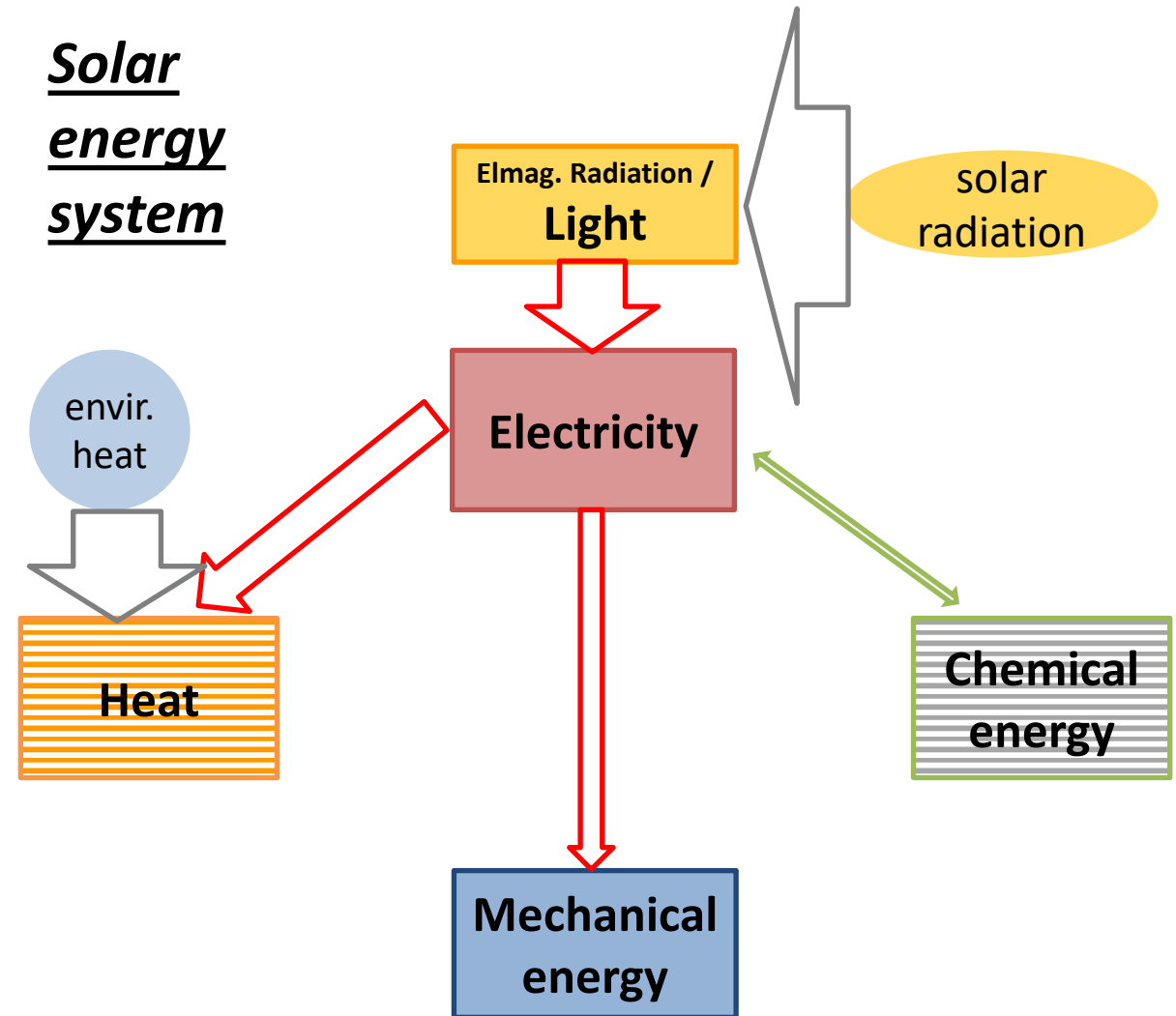


Abandoning fire as basis of our civilisation

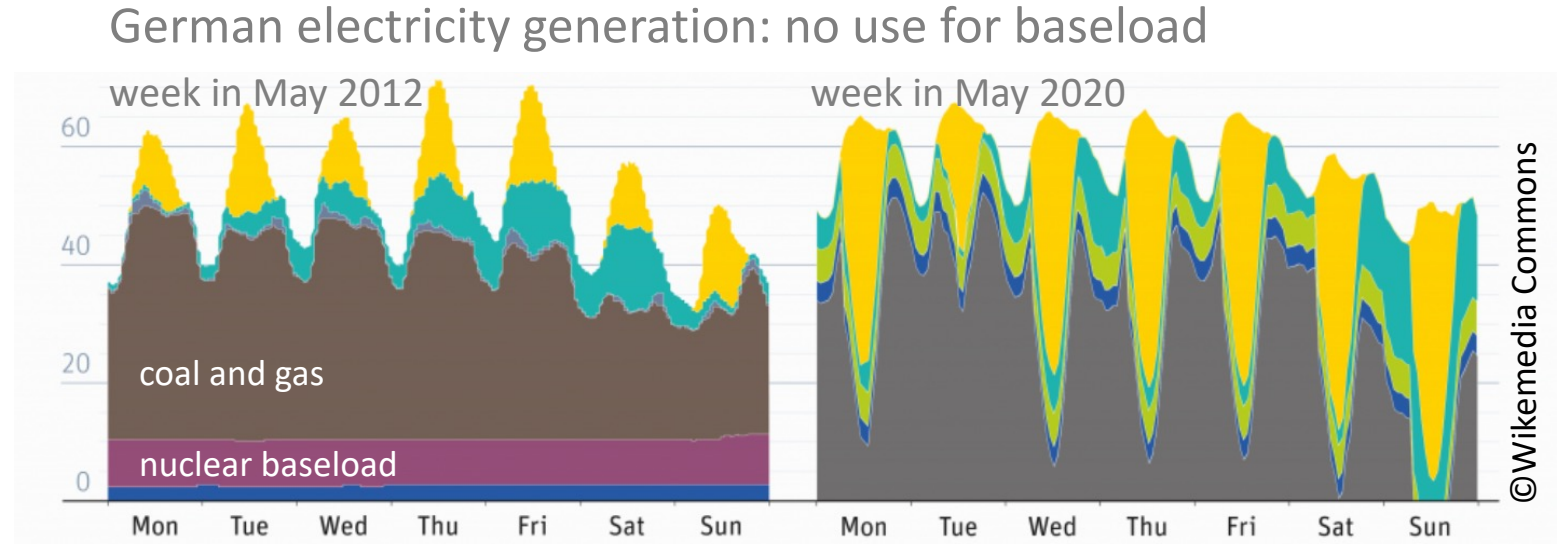
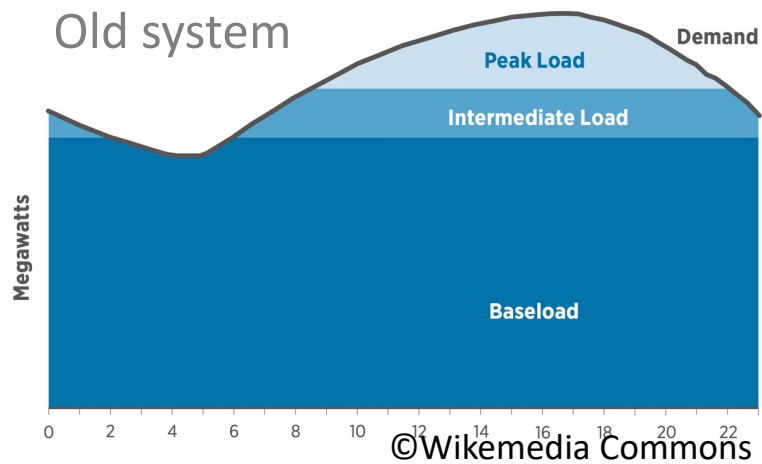
Fossil energy system



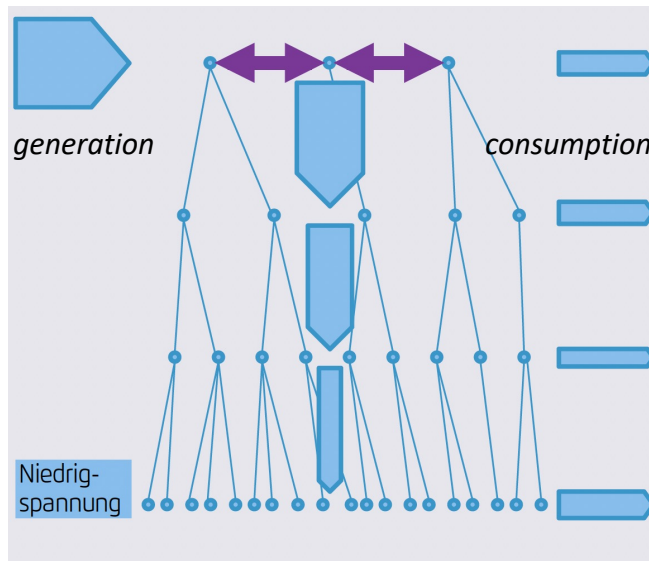
Solar energy system



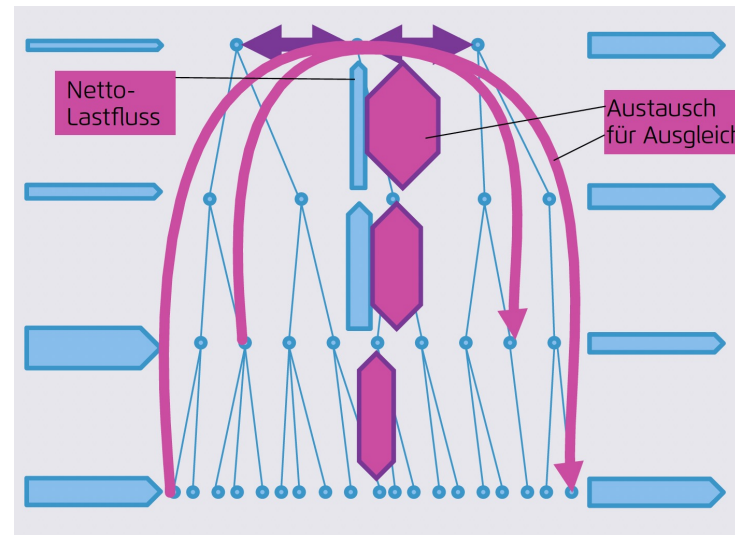
System Transformation



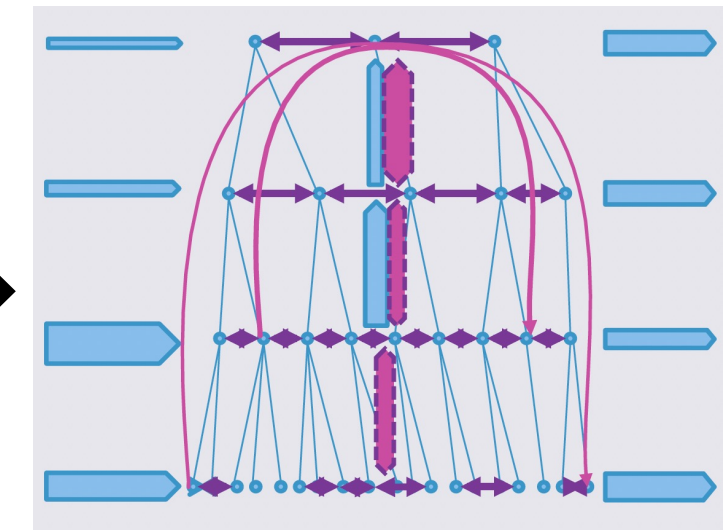
old system
central generation



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

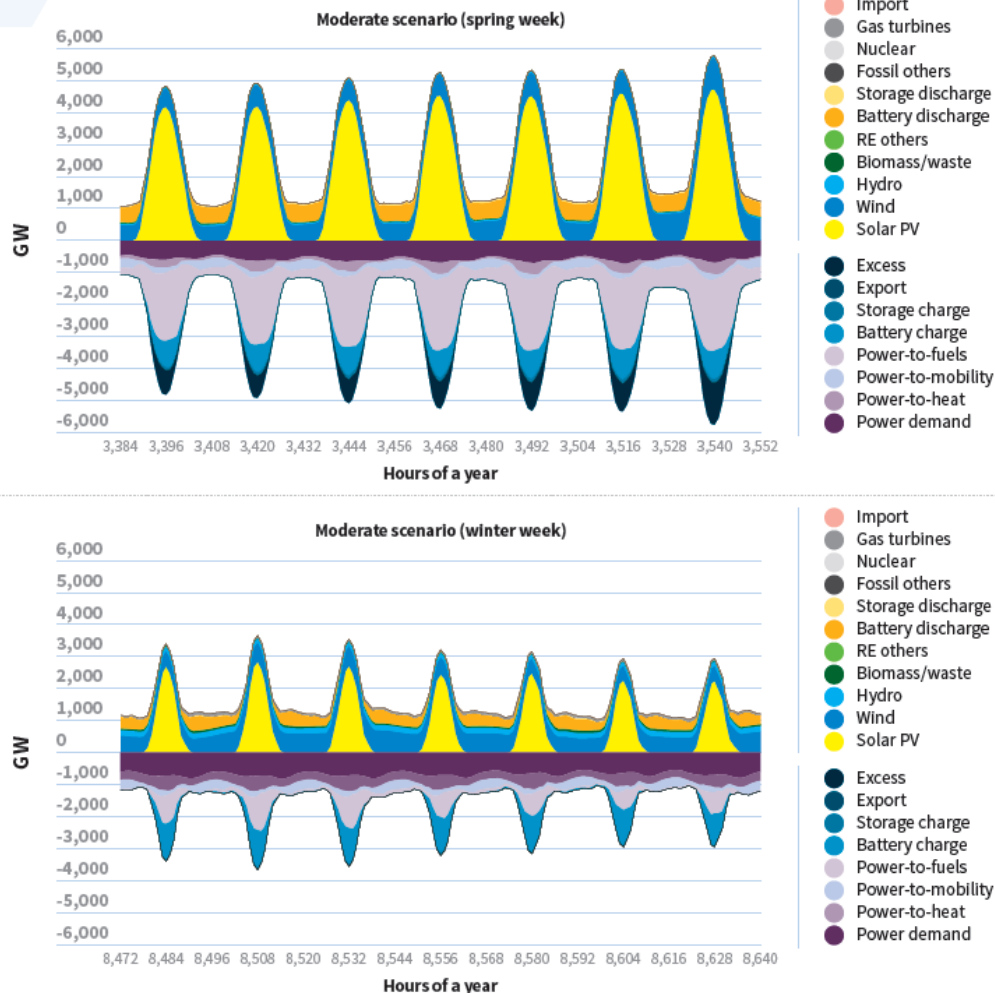
Those countries or regions who insist to stay with the old one will suffer increasing disadvantages

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:

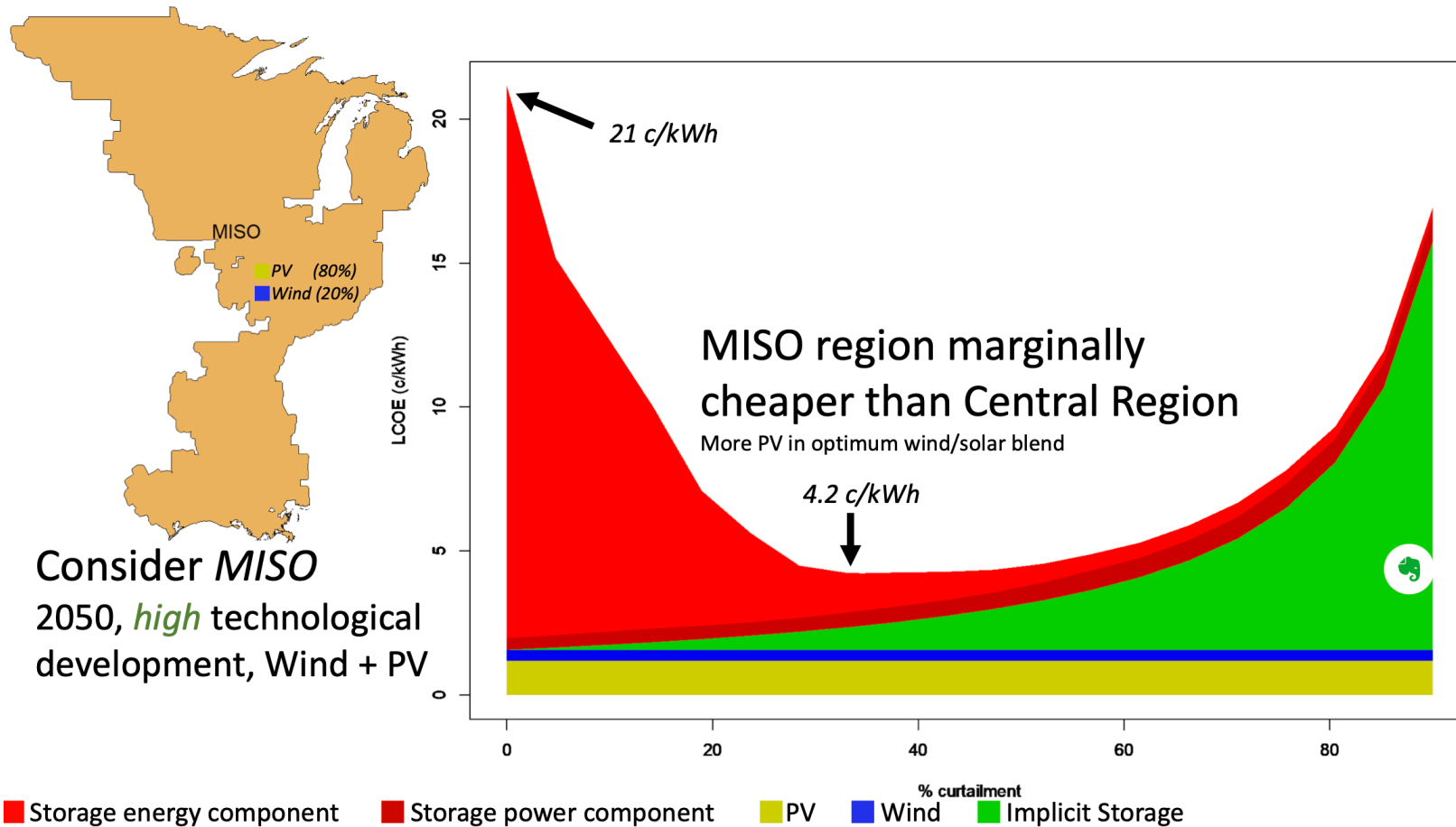
- Week of least renewables supply (winter) and most renewables supply (spring) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the country easily copes with energy demand
- Key balancing component are electrolyzers (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

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

[Link to source](#)

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

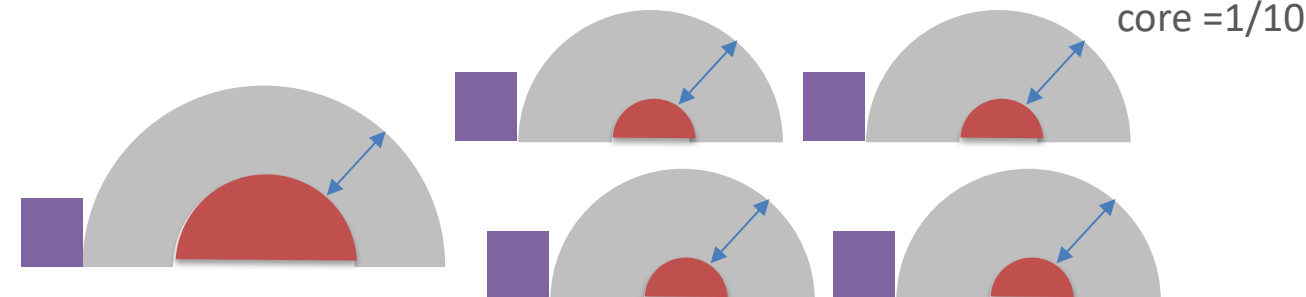
- Possibly increased inherent safety countervailed by new risks
- Multitude of plants and transports more susceptible to external threats
- Missing safety criteria for new concepts with molten metals, reprocessing, liquid fuel, high temperatures, new dynamics
- Reduced number of safety barriers

Basic issues of nuclear power remain:

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

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]



Nuclear is definitely an outdated technology

Too costly

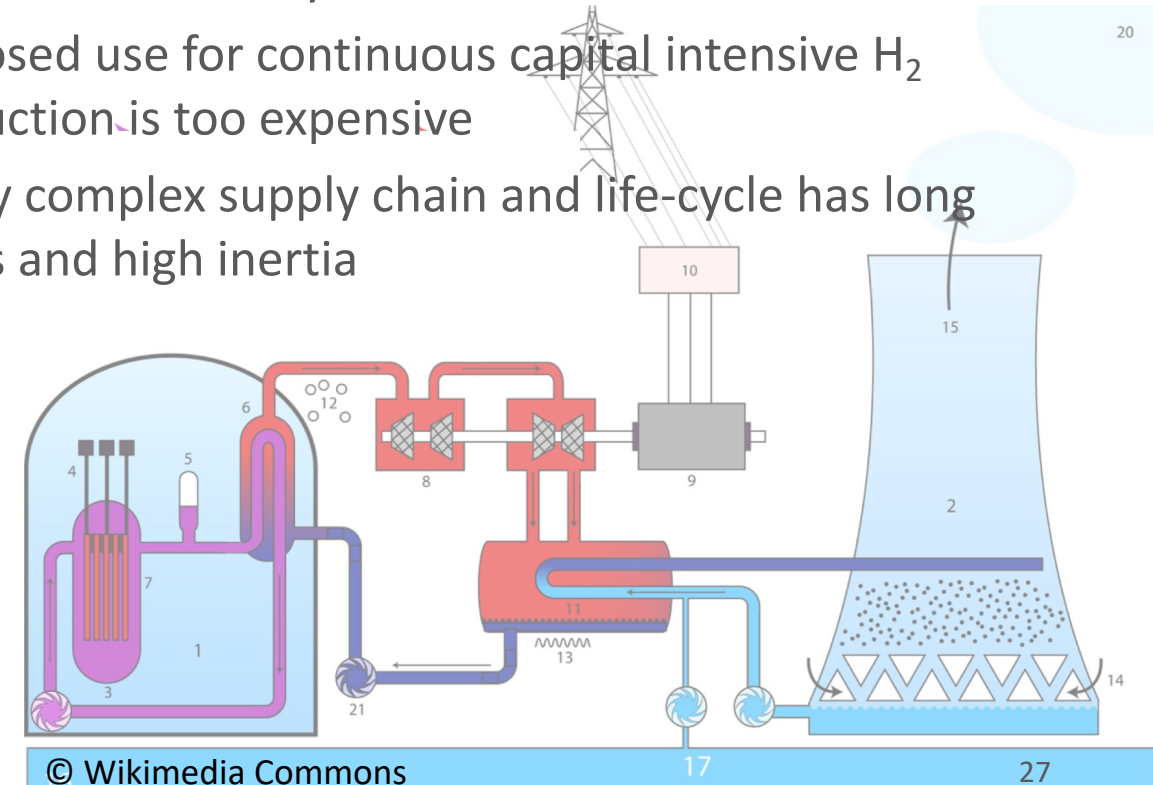
- Nuclear, new large : 13 – 20 ct/kWh →
- Low chance of SMRs being cheaper ↗
- Old nuclear operation : 2,9 ct/kWh ↗
- PV power plants : 1 – 4 ct/kWh ↘
- Battery : 150 €/kWh capacity, assume 7k cycles → 2,1 ct/kWh ↓
- PV + Battery & assumptions, <8ct/kWh

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 H₂ production is too expensive
- Highly complex supply chain and life-cycle has long cycles and high inertia



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

Unknown author, via Wikimedia Commons

- 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

Stefan Kühn, [CC BY-SA](#) via Wikimedia Commons

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?

Thank you for your attention

www.sustainablestrategies.eu

more details concerning this subject in my blog:

sustainablestrategies.substack.com