Energy Economics, Winter Semester 2026-7
Lecture 1: Organisation & Introduction

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Department of Digital Transformation in Energy Systems, Institute of Energy Technology, TU Berlin

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Table of Contents

1. Administration

2. History and Definition of Energy Economics

3. Energy Economics Defined by Crises

4. Introduction to Energy Transitions

Administration

Team Details

Technische Universität Berlin

Prof. Dr. Tom Brown

Department of 'Digital Transformation in Energy Systems', Institute of Energy Technology

I specialise in the modelling of energy systems to meet strict greenhouse gas emission targets. I work at the intersection of engineering, economics, informatics, mathematics & meteorology.

Dr. Fabian Neumann is a scientist in the group and will lead the tutorials; he can also answer any organisational questions (**f.neumann@tu-berlin.de**).

Group website: **https://www.tu.berlin/ensys**

Personal website: **https://nworbmot.org/**

Course Website

You can find lecture notes, exercise sheets and all other information on ISIS:

https://isis.tu-berlin.de/course/view.php?id=49201

Course ISIS name: [WiSe 2026/27] Energy Economics

Announcements will also be made there, and you can ask questions in the discussion forum.

Lecture slides will be available shortly before each lecture and online until after the exam.

Old video recordings of the lectures from 2022/3 will also be available.

Course Structure: 6 ECTS

The course has 6 ECTS.

Registration:

- via MTS (up to one week before the exam)
- Erasmus: try via MTS, if that fails, email Dr. Fabian Neumann

Written exam in presence

- 90-minute written exam in presence
- First exam on 15.02.2027, second exam/resit on 02.04.2027
- No materials may be used in exam except calculator
- Sample exam in the last week of lectures
- Content: as in lecture and tutorials
- Voluntary group project (six unsupervised study periods in Jan) can boost grade by 5 points (5% of total)

SoSe 27: Course ‘Energy Systems’

6 ECTS course led by me and Dr. Fabian Neumann.

- Whereas ‘Energy Economics’ focuses on present and near-term, ‘Energy Systems’ looks to the future
- How do we design an energy system for climate neutrality?
- Focus on managing renewable variability in space and time
- Storage, demand-side management, and coupling to transport, buildings and industry
- Deep-dives on time series, grid modelling and optimisation theory

SoSe 27: Course ‘Data Science for Energy System Modelling’

6 ECTS course led by Dr. Fabian Neumann.

- Students get hands-on experience modelling and analysing future energy systems
- All coursework in programming language Python plus associated libraries
- Focus on renewable energy resources, storage and network infrastructures
- Working with real data on weather, land use, power plants, grids and demand
- Learn about the challenges and solutions for a successful transition towards climate-neutral energy systems across the globe

Schedule for Lectures and Tutorials

Day	Time	Location	Event
Tuesday	1400-1600	MA 005	Lecture
Thursday	1400-1600	MA 004	Lecture
Thursday	1600-1800	HFT-TA 131	Tutorial

First lecture: Tuesday 13th October 2026, last lecture: Thursday 11th February 2027

First tutorial: Thursday 29th October 2026, last tutorial: Thursday 11th February 2027

Group work

- Voluntary group work (up to 5 students)
- 6 study periods instead of lectures and exercises
- Probably starting 04. or 11.01.2027
- Programming needed (can use Python/Matlab/R)
- Report and presentation
- Boost grade by up to 5 points (5%)
- Rewards: Deeper understanding of the topic, methodological competence and extra bonus points for the exam

Literature

There is no book which covers all aspects of this course; the world of energy markets is also changing fast. The following are at least concise:

- G. Erdmann, A. Praktiknjo, P. Zweifel, "Energy Economics - Theory and Applications," Springer, 2017
- M. Grubb et al, "Planetary Economics," Routledge, 2013, **available online**
- S.C. Bhattacharyya, "Energy Economics. Concepts, Issues, Markets and Governance," Springer, 2011
- D.R. Biggar, M.R. Hesamzadeh, "The Economics of Electricity Markets," Wiley, 2014
- C.A. Dahl, "International Energy Markets: Understanding Pricing, Policies, and Profits," PennWell, 2004
- S. Stoft, "Power System Economics: Designing Markets for Electricity," IEEE Press. 2002

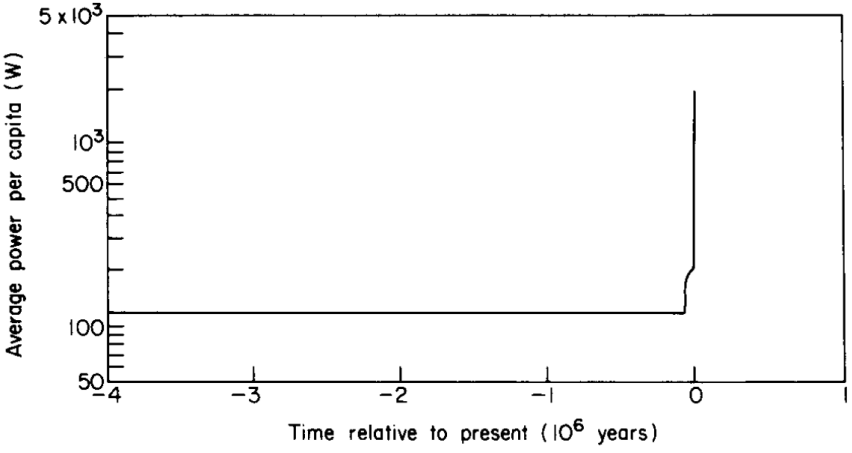
Course outline

- Measuring energy, energy balances
- Basics of microeconomics
- Financial management
- Electricity markets
- Electricity grids
- Supporting renewables
- Emissions markets
- Resource management
- Oil markets
- Gas markets
- Learning curves and long-term dynamics
- Sector coupling
- Climate economics
- Current research topics

History and Definition of Energy Economics

Average energy use over time

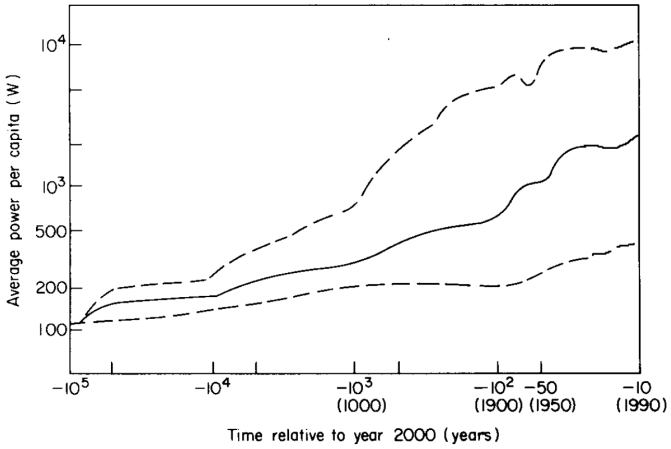
It is hard to exaggerate the historical discontinuity of modern energy consumption.



Source: Sørensen, "Renewable Energy", 1979

Average energy use over time

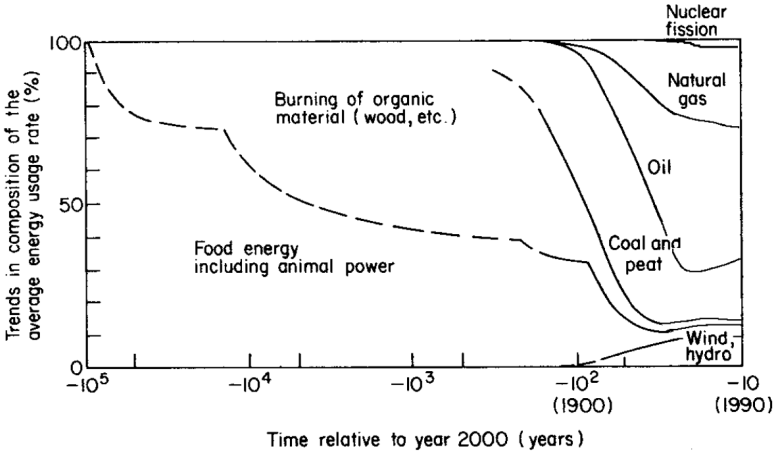
A logarithmic time axis is necessary. Solid line is world average, dashed lines show societies with highest and lowest energy use.



Source: Sørensen, "Renewable Energy", 1979

Several energy transitions

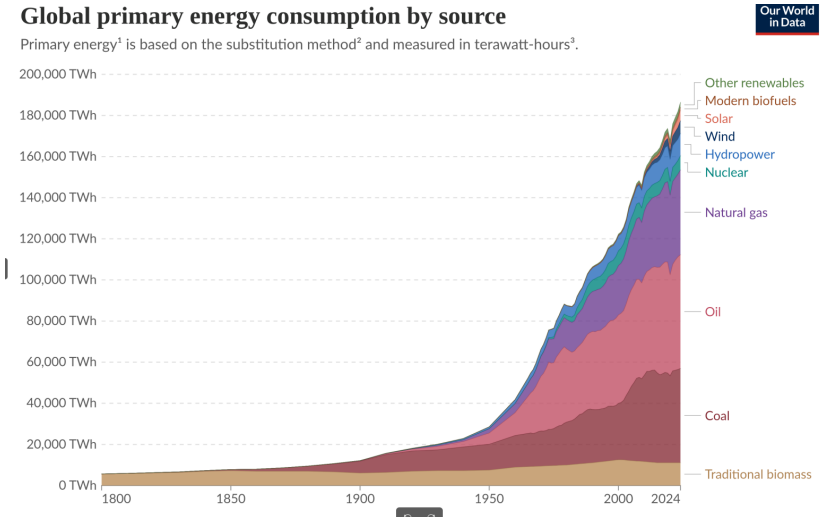
Energy transitions from muscle to biomass to coal to oil and gas, next: low-carbon electricity?



Source: Sørensen, "Renewable Energy", 1979

Primary energy growth

Extraordinary growth in primary energy consumption since 1950s, much in oil and gas.



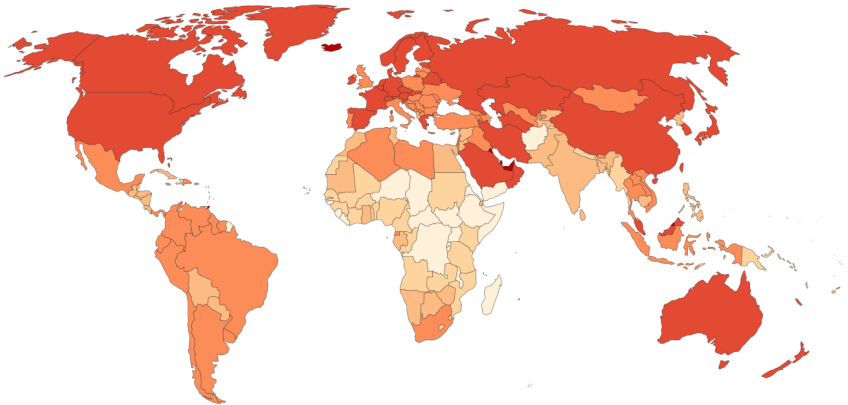
Source: **Our World in Data, 2025**

Primary energy consumption is unevenly distributed

Energy use per person, 2024

Our World in Data

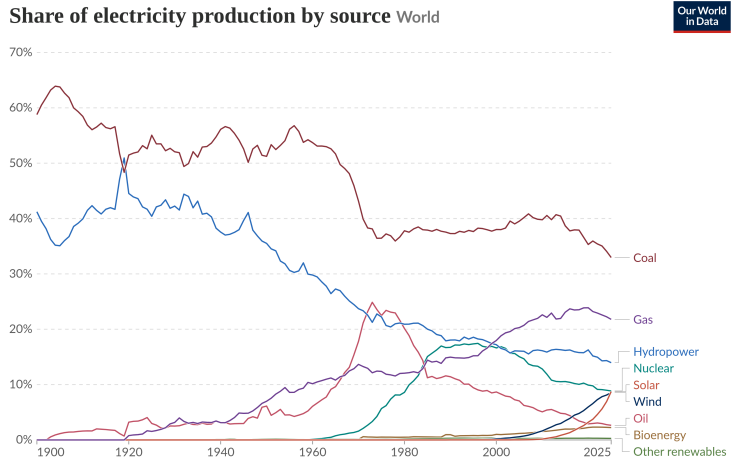
Measured in kilowatt-hours[1] per person. Here, energy refers to primary energy[2] using the substitution method[3].



Source: Our World in Data, 2025

Electricity: rate of change is important

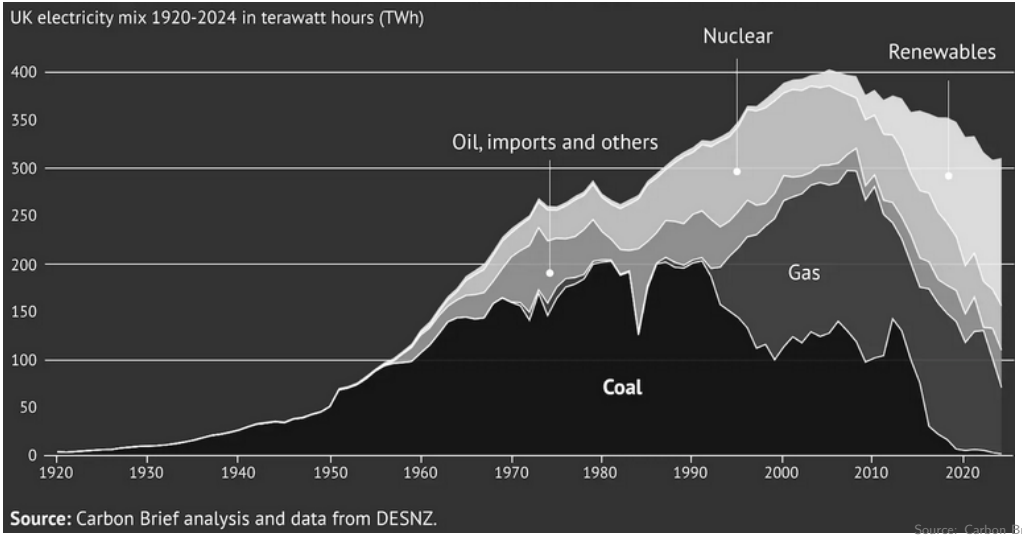
Wind and solar are growing fast, each close to 10% of world electricity in 2025.



Source: **Our World in Data, 2026**

Electricity: rate of change is important

In OECD countries, coal generation pushed out by gas and renewables; ended in UK in 2024.

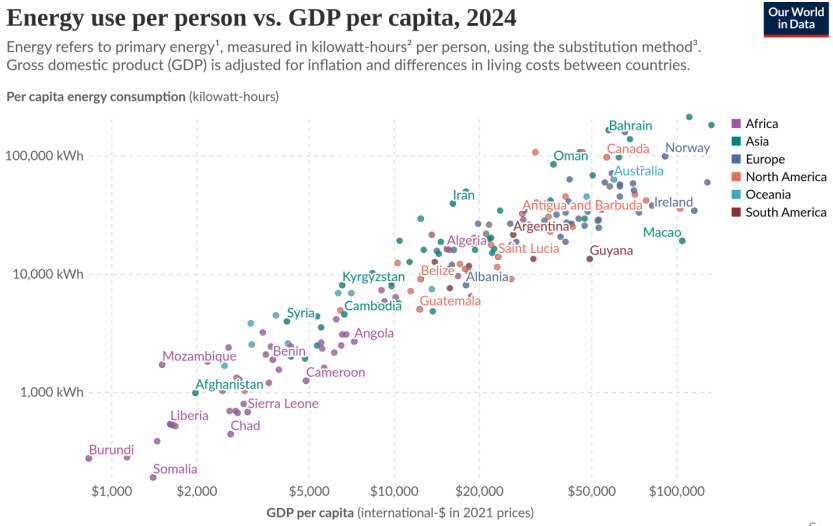


Source: Carbon Brief, 2024

Economic development and energy use go together

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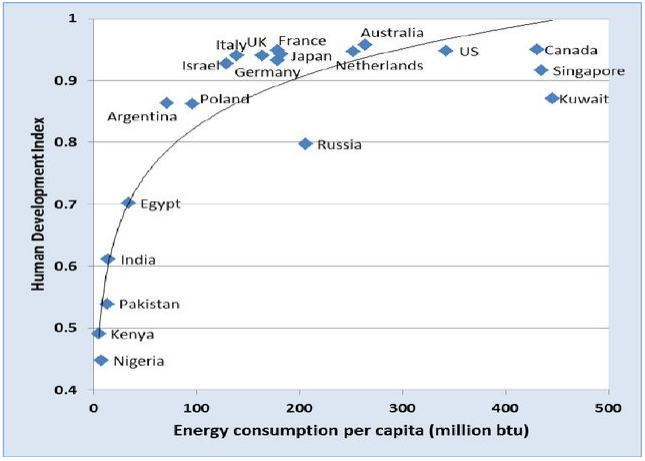
Energy demand versus GDP in 2024 (NB: logarithmic scales).



Source: World In Data, 2025

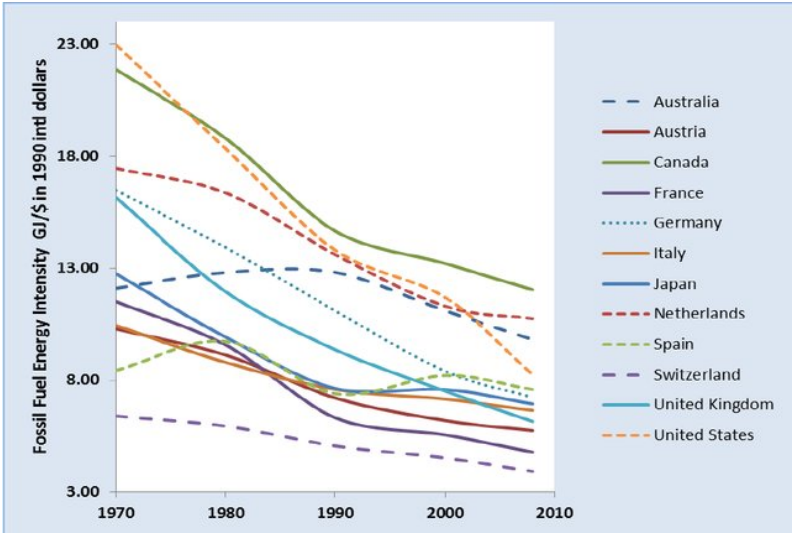
Economic development and energy use go together

Modern prosperity depends on a functioning energy supply for electricity, warmth/cooling, mobility and energy-intensive food and products.



Source: **Slaus & Jacobs**, 2011

Fossil-fuel intensity is decreasing



Source: **Slaus & Jacobs**, 2011

Why ‘energy economics’?

Like any area where there are diverse uses for a good with different value to consumers, as well as scarcity on the supply side leading to different supply costs, markets can play a role in allocating goods. Economics is the study of this allocation.

This raises further questions:

- What makes energy different to other goods?
- Why a whole subject ‘energy economics’?
- Why is energy politically so important?
- How does energy influence geopolitics?
- What questions does ‘energy economics’ try to answer?

What makes energy economics different from regular economics?

The unique features of energy are numerous:

- **Essential for modern life**: for farming, cooking, lighting, comfort in buildings (heating and cooling), communication, mobility, production of most goods. This makes it a **political concern**.
- **Essential to all economic activity**. Cf. negative economic consequences of electricity blackouts in South Africa, European gas crisis of 2021-2022.
- Reserves of fossil fuels and production capacity/minerals for renewables & storage are **concentrated in a few countries**. Geopolitics!
- **Large externalities**: most greenhouse gas emissions come from use of fossil fuels in energy, leads to climate breakdown; air pollution leads to widespread health impacts; for nuclear in meltdown and waste risk; for renewables in landscape impact.
- **High potential for innovation and cost reduction**: wind, solar, batteries, electrolysers.

What makes energy economics different from regular economics?

- Energy is **abundant** in nature, but mostly not immediately available for doing useful work.
- Infrastructure (transmission, generators) requires **long periods** of planning, investment and operation. Leads to slow change - inertia!
- In many markets there are **monopoly structures**, which are resistant to market solutions and need regulation (e.g. transmission networks, but also vertically-integrated utilities in some regions).
- Infrastructure **property rights** (e.g. underground, hydro) are sometimes with public rather than private sector.
- Some **risks are diffuse and widespread** (nuclear, hydro, landscape impact of wind).

Source: Zweifel et al, Energy Economics, 2017

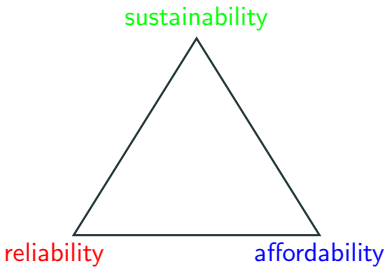
What questions does energy economics try to answer?

Here is a typical selection of energy economics questions:

- How do we allocate consumption and production of energy by existing assets (short run)?
- How should we investment in energy consumption and production assets in the long run?
- How can we most efficiently reduce greenhouse gas emissions and air pollution from the energy sector?
- Wind and solar power are low-cost, but how do we efficiently deal with their variability?
- How do we design markets for variable renewable energy?
- Is a decentral system design better than a centralised one?
- Can we protect vulnerable consumers from energy market volatility?

Guidelines for Energy Policy: Trilemma

What should a well-functioning energy system look like? We design with respect to three goals:

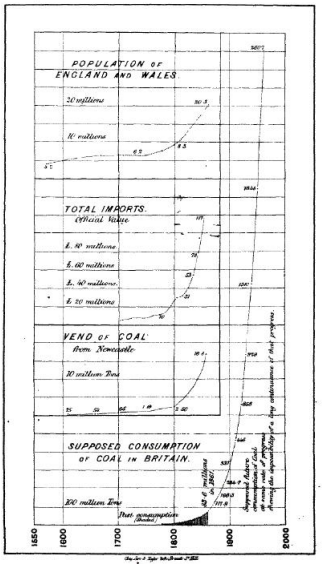


- **Sustainability**: Respect environmental constraints (greenhouse gases, air quality, preservation of wildlife), as well as social and political constraints (public acceptance of transmission lines, onshore wind, nuclear power)
- **Reliability**: Ensure energy services are delivered whenever needed, even when the wind isn't blowing and the sun isn't shining, and even when components fail
- **Affordability**: Deliver energy at a reasonable cost

Some of these policy targets can come into **conflict** - an **energy trilemma**.

Energy Economics Defined by Crises

History of energy economics: Jevons' Coal Question in 1865

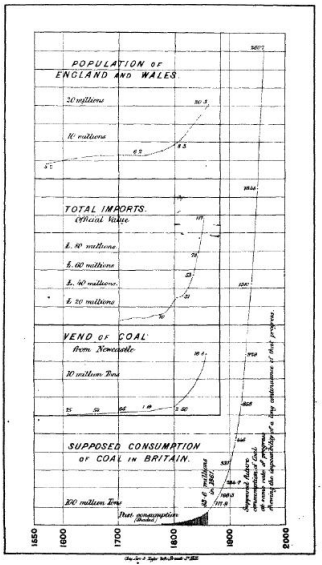


In 1865 William Stanley Jevons published **The Coal Question**, whose concern was the exhaustion of coal reserves in Britain given exponentially rising demand.

- "With coal almost any feat is possible or easy; without it we are thrown back into the laborious poverty of early times."
- "I must point out the painful fact that such a rate of growth will before long render our consumption of coal comparable with the total supply. In the increasing depth and difficulty of coal mining we shall meet that vague, but inevitable boundary that will stop our progress."
- He reviews renewables, including wind used to pump water up into reservoirs, and also green hydrogen, before dismissing them all.

Source: Jevons,1865

History of energy economics: Jevons' Coal Question in 1865

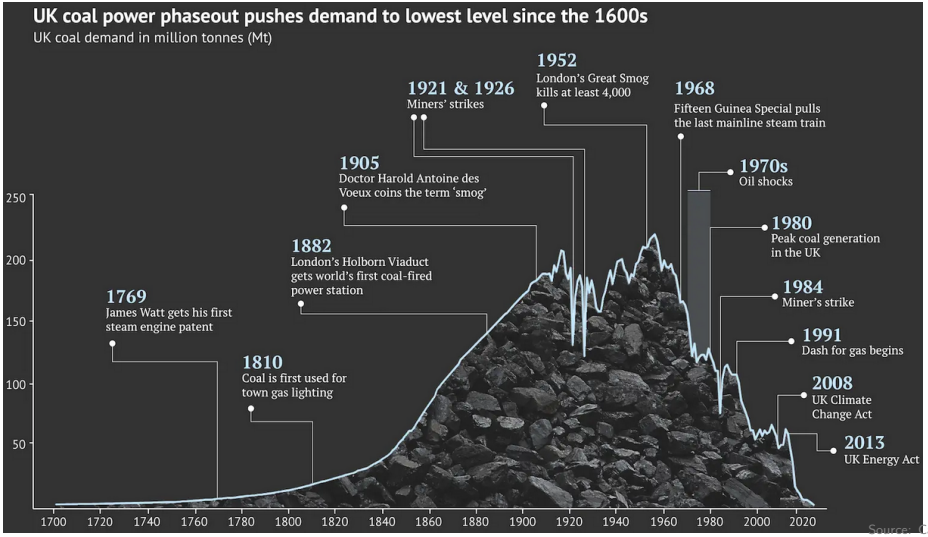


- **Jevons' Paradox**: "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth...Whatever, therefore, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations."
- "If we lavishly and boldly push forward in the creation and distribution of our riches, it is hard to over-estimate the pitch of beneficial influence to which we may attain in the present. But the maintenance of such a position is physically impossible. We have to make the momentous **choice between brief greatness and longer continued mediocrity**."

Source: Jevons, 1865

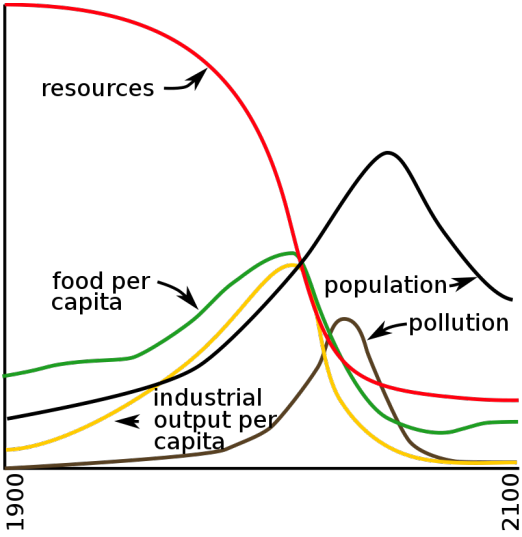
Coal in the UK: what actually happened

1865 was roughly the time the exponential growth flattened out into a standard **S-curve**.



Source: Carbon Brief, 2024

1972: Limits to Growth



1972 report **The Limits to Growth**, commissioned by the Club of Rome, examined consequences of exponential economic and population growth with a finite supply of resources with a computer simulation.

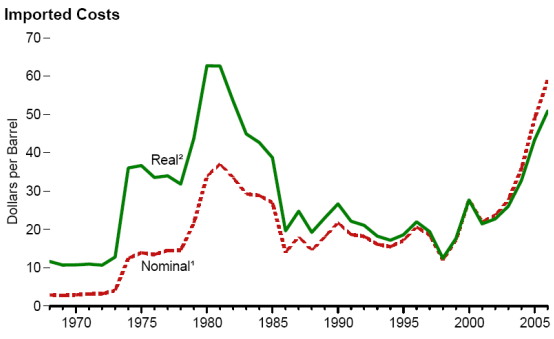
- Conclusion: "the most probable result will be a rather **sudden and uncontrollable decline** in both population and industrial capacity".
- But ignores role of technological progress.
- Growth versus limits versus progress: debate continues today.

Source: Limits to Growth

1970s oil crisis

In 1973 OPEC led by Saudi Arabia embargoed oil in response to the Yom Kippur War. Oil price jumps from 4 to 12 USD/barrel, before rising further in 1979 crisis following Iranian Revolution.

Fossil fuels are intimately tied to **geopolitics**. Triggered blooming of energy studies.





1973 oil crisis as a catalyst for change

In 1972, 92% of Denmark's energy consumption came from imported oil.

Catalyst for many people (mostly physicists - that's another story) to rethink energy supply: Amory Lovins ('Soft Energy Paths' 1976-7); Art Rosenfeld on Energy Efficiency; Union of Concerned Scientists report 'Energy Strategies: Toward a Solar Future' (1980); Bent Sørensen; Swedish Secretariat for Futures Studies; Le Groupe de Bellevue, ALTER: A Study of a Long-Term Energy Future for France based on 100% Renewable Energies (Paris, 1978); Wolf Häfele, Jeanne Anderer, A. McDonald and Nebojsa Nakicenoviç, Energy in a Finite World (Cambridge, MA: Ballinger, 1981), many others...

1975: Bent Sørensen: 1st consistent 100% RE scenario

In 1975 Bent Sørensen published a scenario for 100% renewable energy in Denmark. He dealt with the variability of wind (with hydrogen) & solar thermal (with TES).

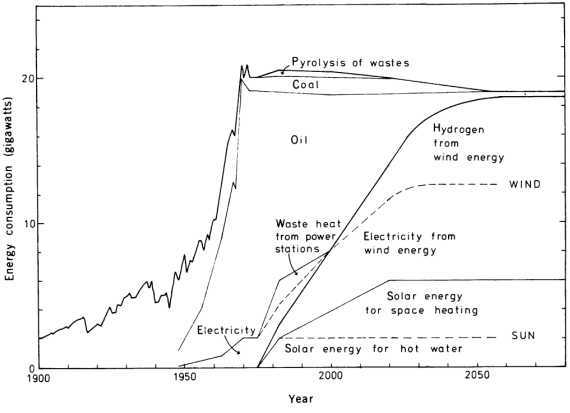


Fig. 4. Net energy consumption in Denmark, shown according to sources. Up to 1974, actual data are shown (*14*); data after 1974 indicate the proposed plan. The relative weighting between solar and wind energy shares might be altered, for example, if a major breakthrough occurred in the development of solar cells, making them competitive to wind-produced electricity under Danish conditions. The heavy, solid line indicates the proposed total share of solar and wind energy.

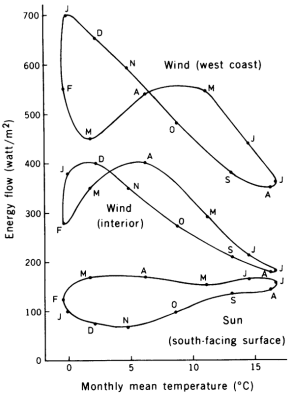
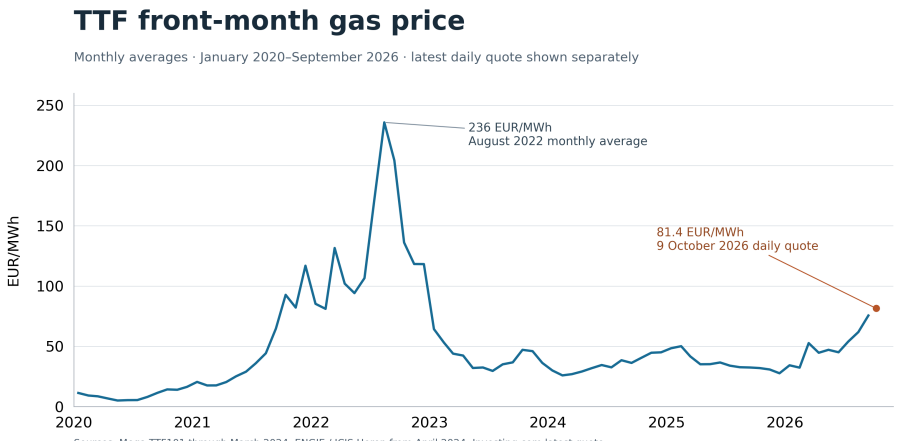


Fig. 2. Monthly average energy flow from continuous sources through a vertical square meter in Denmark, as function of the monthly mean temperature. The sun's height over the horizon at noon is 11° at winter's solstice. The wind data are taken 25 meters above smooth ground.

Source: Sørensen (1975) Science

Gas crisis of 2021-22; replay in 2026?

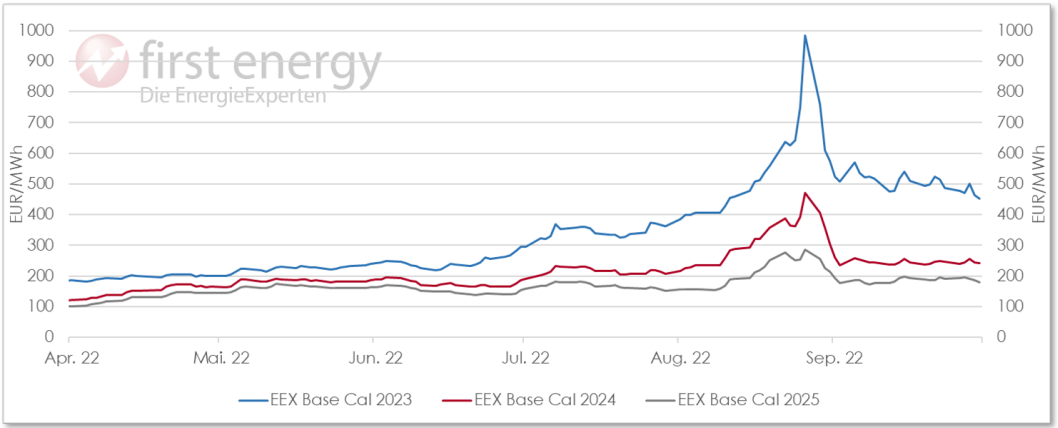
Russian re-invasion of Ukraine led to a geopolitical crisis, halt to almost all Russian gas imports and gas price peaks in 2022 of 17 times the previous equilibrium price.



Source: ChatGPT, 2026

German 2022 electricity prices were six times higher than 2020

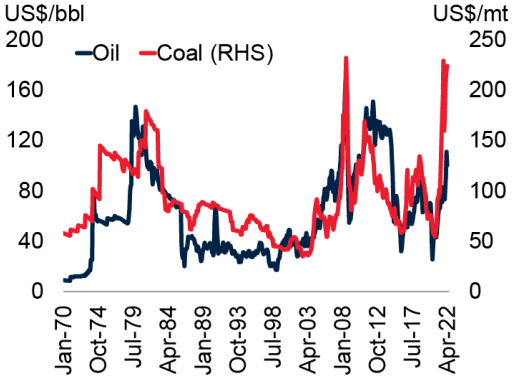
Gas powerplants often set the price in European electricity markets, leading to exploding prices.

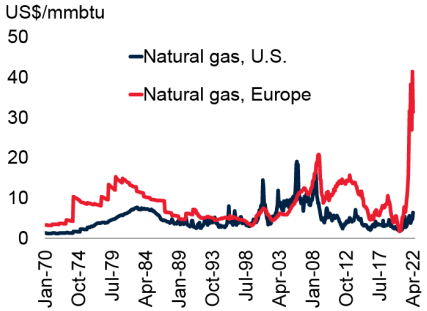


Source: First Energy, 2022

2022 was biggest energy market crisis since 1970s (or ever?)

All major energy carriers were hit in the 2022 crisis: oil, coal, gas and electricity. ('Real prices' means inflation-adjusted prices, as opposed to non-adjusted 'nominal prices'.)





Source: World Bank, 2022

Impact of gas crisis is worldwide thanks to global LNG market

Demand response to high LNG prices varied widely among the main importers in Asia

Gas demand impacts of high spot LNG prices across Asia

Pakistan — 23 TWh
- Deep energy crisis with economy-wide implications
- Rolling blackouts of up to 12 hours
- LNG imports down 19% y-o-y in January-August 2022
- Spot LNG purchases down to a bare minimum
- Oil-fired generation up fivefold

Bangladesh — 7 TWh
- No spot LNG purchases in July-August 2022
- Load shedding of up to 20% in mid-July
- Mandatory conservation measures

India — 47 TWh
- Power sector gas burn down 28% y-o-y in January-August 2022 (partly replaced with coal)
- Reduced gas use in refining (down 29%) and chemicals (down 23%) mostly replaced with oil



China — >90 TWh
- Power sector gas use down by 9% y-o-y in January-August 2022
- Evidence of demand destruction in industry and transport

Japan — 0 TWh
- Accelerated restart of 7 nuclear reactors from mid-2023
- Contingency plan for LNG supply cut scenario

Korea — 10 TWh
- Voluntary coal restrictions suspended for summer 2022
- Accelerated start-up of new coal-fired and nuclear units

Thailand — 11 TWh
- Power sector gas burn down by 6% y-o-y in January-July 2022, diesel generation up 16-fold
- Buy tenders cancelled or unawarded due to high price

Legend:

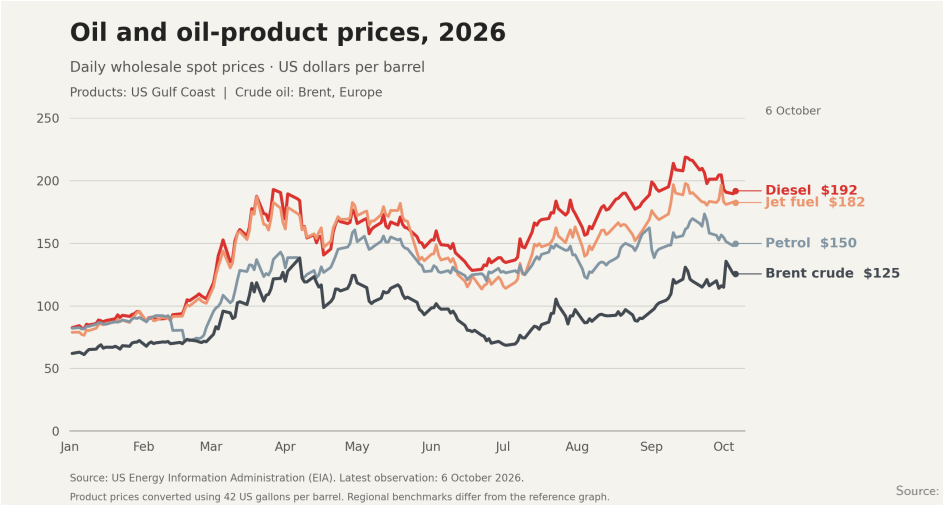
Primarily demand destruction | Primarily fuel-shift

Graph from IEA Gas Outlook 10/2022, preliminary numbers added

Source: IEA via Karsten Neuhoff, 2022

2026 oil crisis after US/Israeli attack on Iran

Huge consequences, especially in Asia where e.g. in India people rely on Liquefied Petroleum Gas (LPG) for cooking; many forced into working from home.



Source: ChatGPT, 2026

Today: urgent need for energy market reform

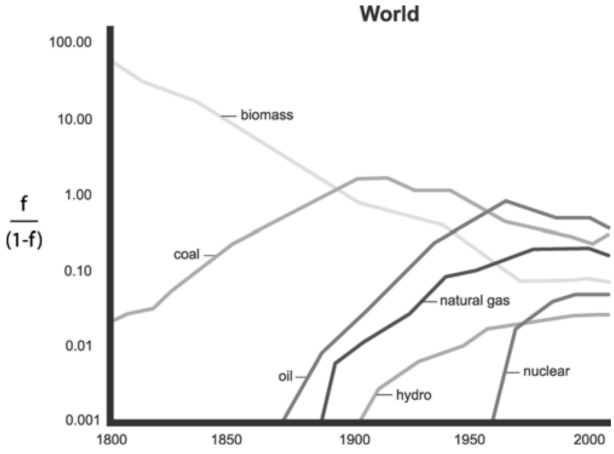
The list of necessary reforms is long and diverse:

- Current tax and subsidy structure: e.g. electricity heavily taxed compared to gas and oil for heating, hindering switch to heat pumps (solutions: reduce EEG-Umlage/Stromsteuer, raise CO_2 price on fossil fuels, subsidise heat pumps)
- Insufficient incentives for flexible demand and storage
- Expansion of wind and solar too slow in many regions
- More locational signals for demand and supply coordination
- Need more incentives for building renovations
- Further digitalisation of energy use and supply
- Investment incentives for decarbonisation of industry, hydrogen infrastructure

Introduction to Energy Transitions

Historic Energy Transitions: Biomass to Hydrocarbons and Electricity

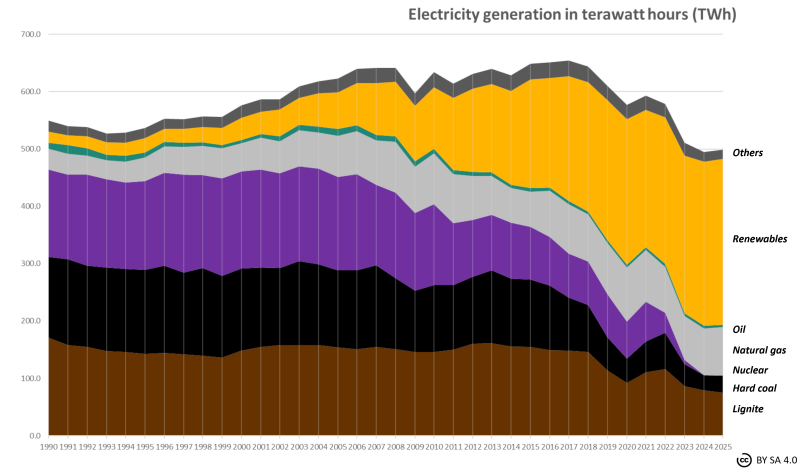
From 1800 to 2010 biomass dominance replaced by hydrocarbons and electricity. Fossil fuel shares steady since 1970. f is fraction of primary energy supply.



Source: Vaclav Smil, "Energy Transitions", 2010

Renewables reached 56% of gross electricity in Germany in 2025

Gross electricity production in Germany 1990 - 2025, by source.
Data: AGEB 2025.



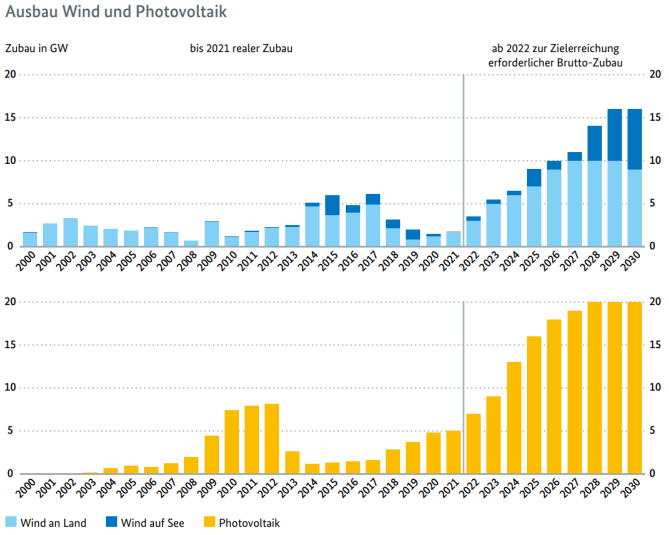
BY SA 4.0

Source: Clean Energy Wire, 2026

Build-out rates for wind and solar need to increase rapidly

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Germany has a target of 80% renewable electricity by 2030, 100% by 2035.



Source: BMWK, 2022

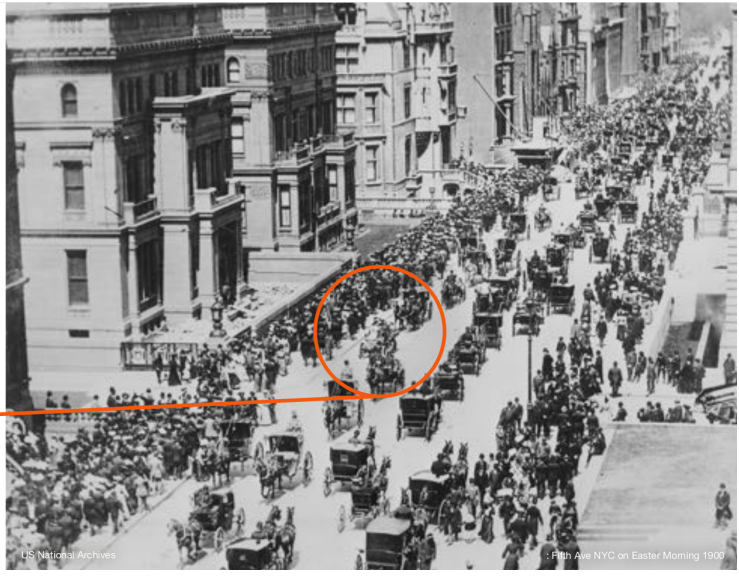
1900: Where's the car?

5th AVE NYC

1900

Where is

the car?



US National Archives : Fifth Ave NYC on Easter Morning 1900

Copyright © 2016 Tony Seba

1913: Where's the horse?

5th AVE NYC

1913

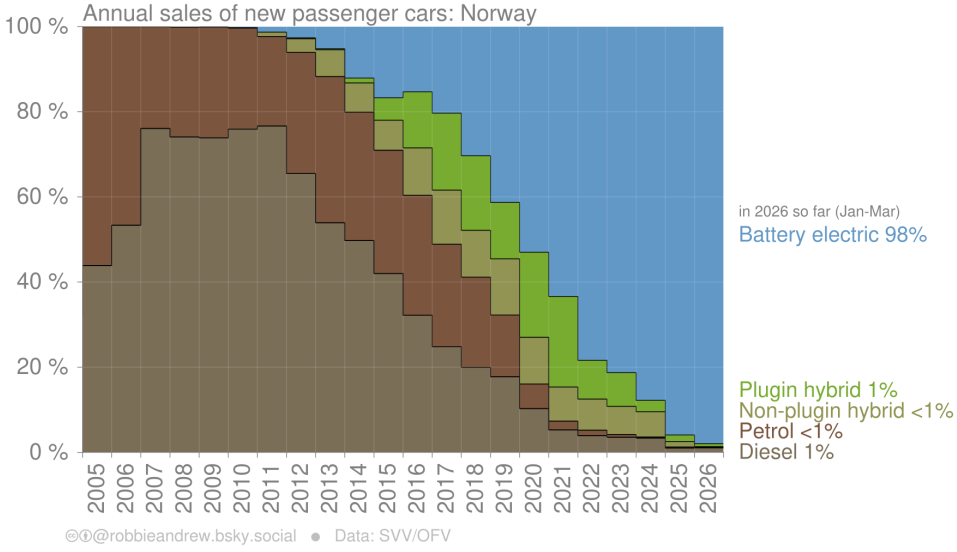
Where is **the horse?**



Photo: Easter 1913, New York. Fifth Avenue looking north.

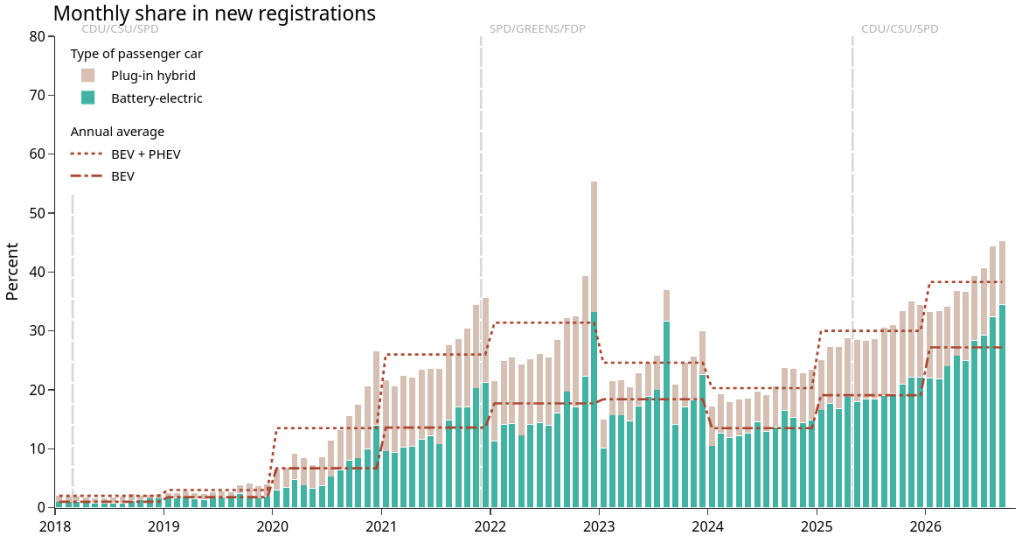
Copyright © 2016 Tony Seba

Electric vehicles take off, first in Norway



Source: Robbie Andrew, 2026

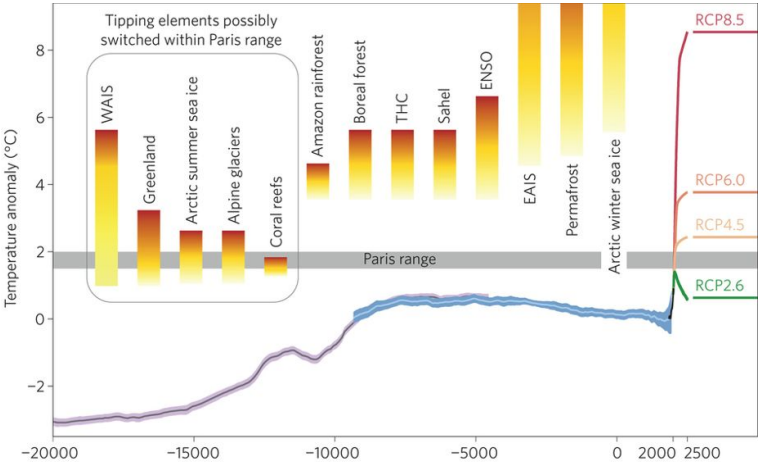
Electric vehicles: Germany catching up?



Source: Open Energy Tracker, 2026

Climate Breakdown: 2015 Paris Agreement

The 2015 Paris Agreement pledged its signatories to 'pursue efforts to limit [global warming above pre-industrial levels] to **1.5°C**' and hold 'the increase...to **well below 2°C**'. These targets were chosen to avoid potentially irreversible **tipping points** in the Earth's systems.



WAIS: West Antarctic Ice Sheet ($\Rightarrow$ 5m sea level rise)

Greenland (7m)

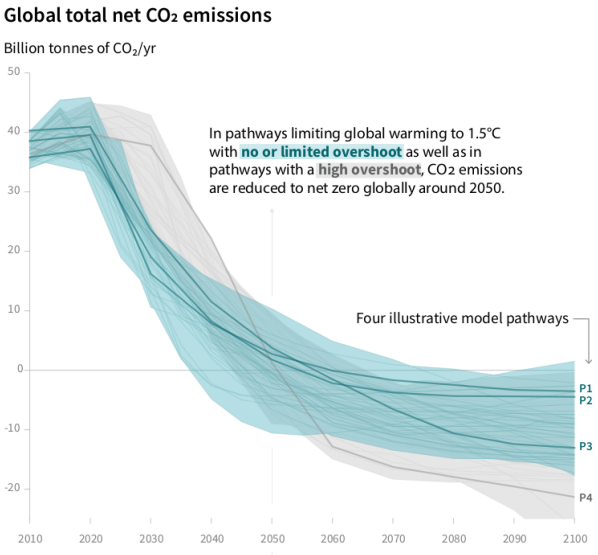
THC: thermohaline circulation (warms Europe)

ENSO: El Niño–Southern Oscillation (extreme weather)

EAIS: East Antarctic Ice Sheet (> 50 m)

Source: **'Why the right climate target was agreed in Paris'**, Nature Climate Change, 2016

The Global Carbon Dioxide Challenge: Net-Zero Emissions by 2050

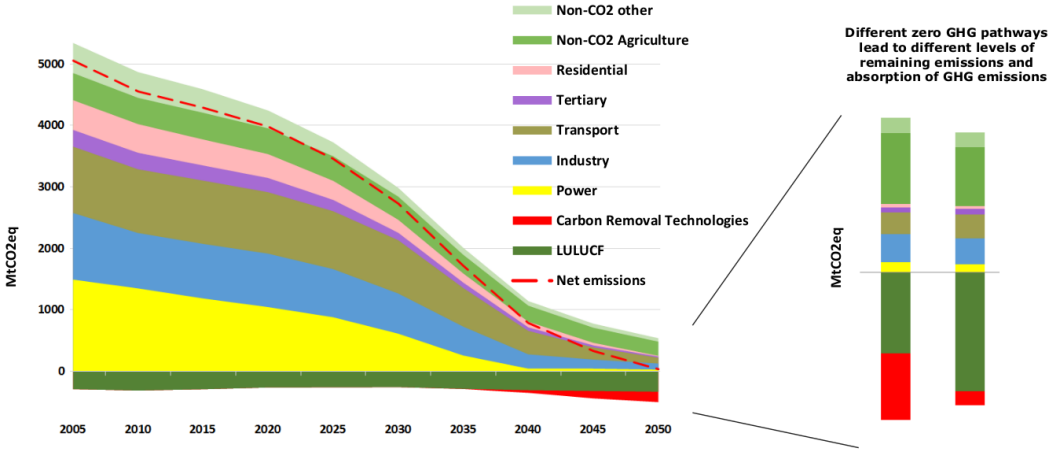


- Scenarios for global CO_2 emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: **net-zero by 2050**

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

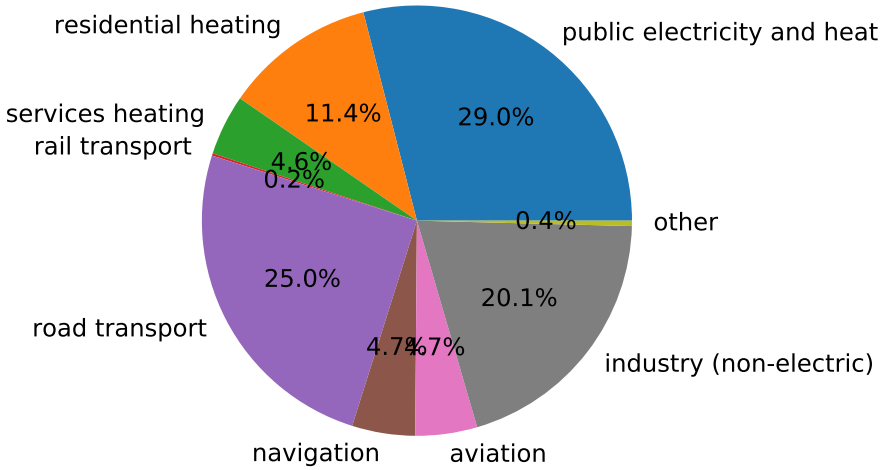
Paris-compliant 1.5° C scenarios from European Commission for **net-zero GHG in EU by 2050**. This target has been adopted by the EU and enshrined in the **European Green Deal**.



Source: European Commission 'Clean Planet for All', 2018

It's not just about electricity demand...

EU28 CO_2 emissions in 2016 (total 3.5 Gt CO_2, 9.7% of global):



Source: Brown, data from EEA

...but electrification of other sectors is critical for decarbonisation

Electrification is essential to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

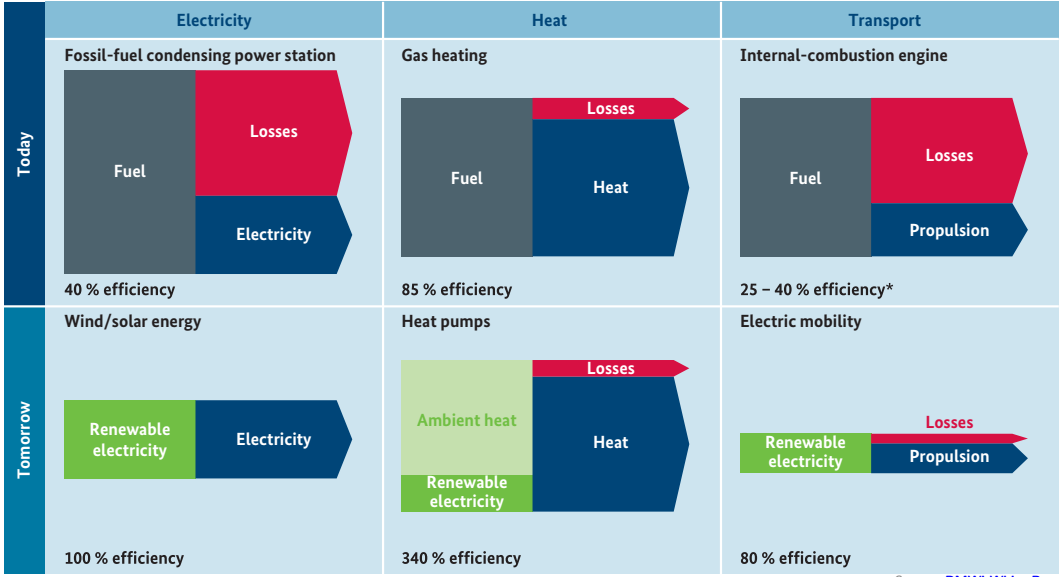
Some scenarios show a **doubling or more of electricity demand**.





Source: Tesla; heat pump: Kristoferb at English Wikipedia

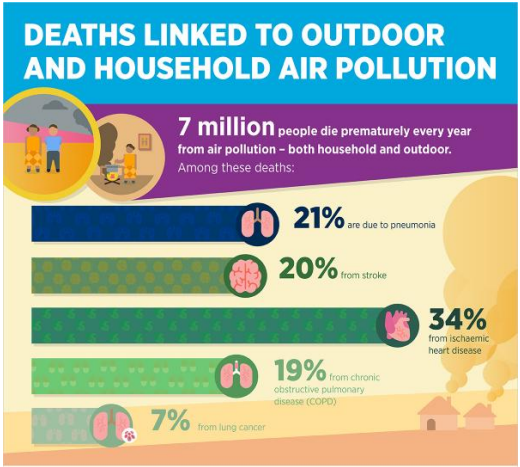
Efficiency of renewables and sector coupling

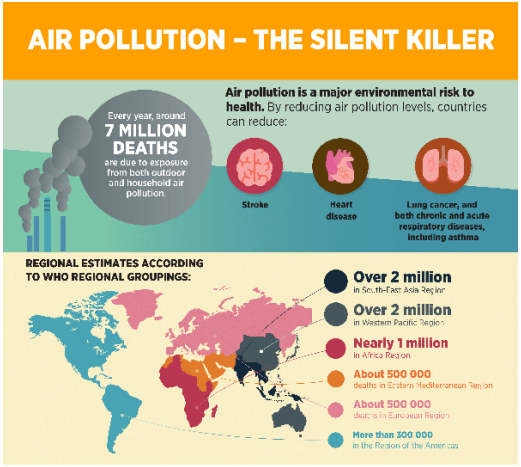


Source: BMWi White Paper 2015

Not just climate change: air pollution is a silent killer

Air pollution from fossil fuel burning is linked to higher mortality (deaths) and morbidity (diseases, e.g. aggravation of asthma).

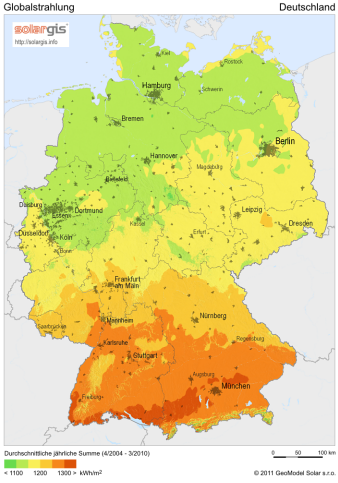


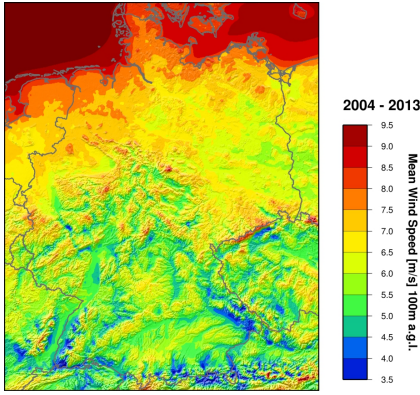


Source: World Health Organisation

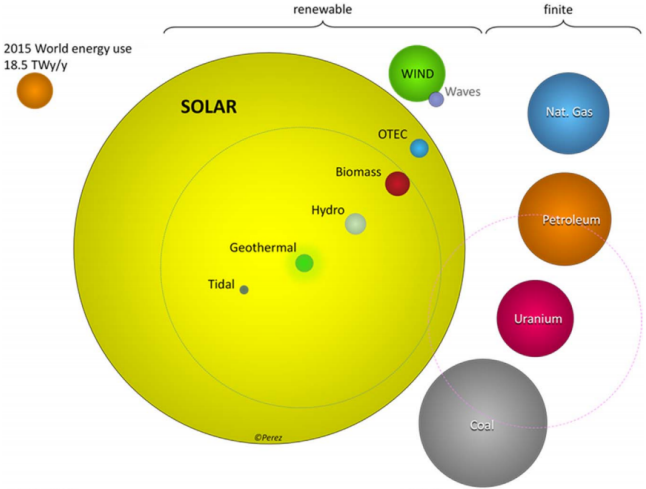
Why focus on wind and solar for electricity generation?

- construction and operation have low greenhouse gas emissions
- good wind and sun are available in many parts of the world
- worldwide potential that exceeds demand by many factors
- rapidly falling costs





Worldwide potentials



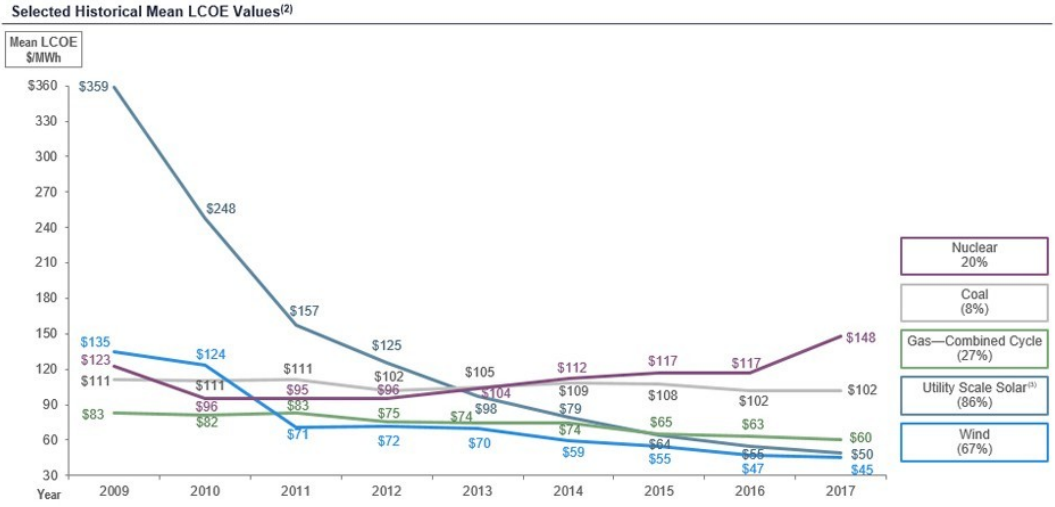
RENEWABLE				FINITE	
Solar	23,000 TWy/y	Biomass	2-6 TWy/y	Nat. Gas	220 TWy
Wind	75-130 TWy/y	Hydro	3-4 TWy/y	Petroleum	335 Twy
Waves	0.2-2 TWy/y	Geotrm	0.2-3++ TWy/y	Uranium	185++ TWy
OTEC	3-11 TWy/y	Tidal	0.3 TWy/y	Coal	830 TWy

- Potentials for wind and solar exceed current demand by many factors (ignoring variability)
- Other renewable sources include wave, tidal, geothermal, biomass and hydroelectricity
- Uranium depends on the reactor: conventional thermal reactors can extract 50-70 times less than fast breeders

Source: Perez et al, Applied Policy, 2016

Low cost of wind & solar per MWh in 2017 (NB: ignores variability)

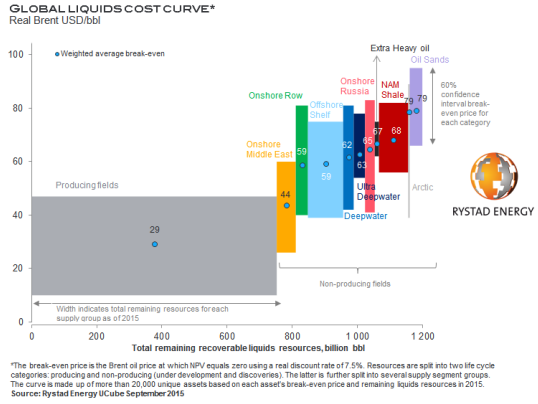
LCOE = **Levelised Cost of Energy** = Total Costs / Energy Output



Source: Lazard's LCOE Analysis V11

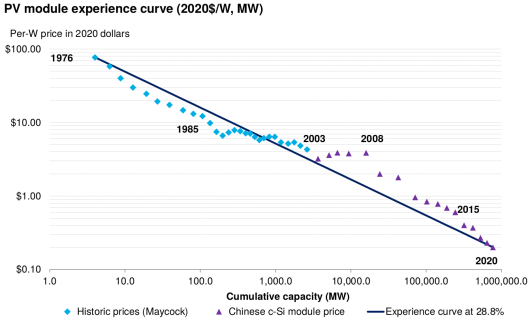
Fundamental shift from scarce exhaustible to renewable energy

Fossil fuel costs rise with exploitation (can also drop with innovation)



(2019 consumption was ∼37 billion barrels)

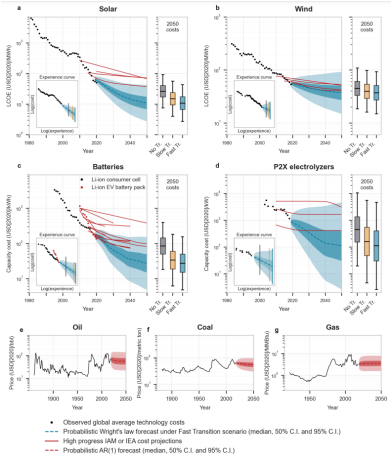
Solar and wind costs drop with innovation (can rise locally where land is scarce)



(1 TW of solar generates ∼1200 TWh/a compared to global electricity demand of ∼24,000 TWh/a)

Source: BNEF 2021

4 critical technologies: wind, solar, batteries, electrolyzers



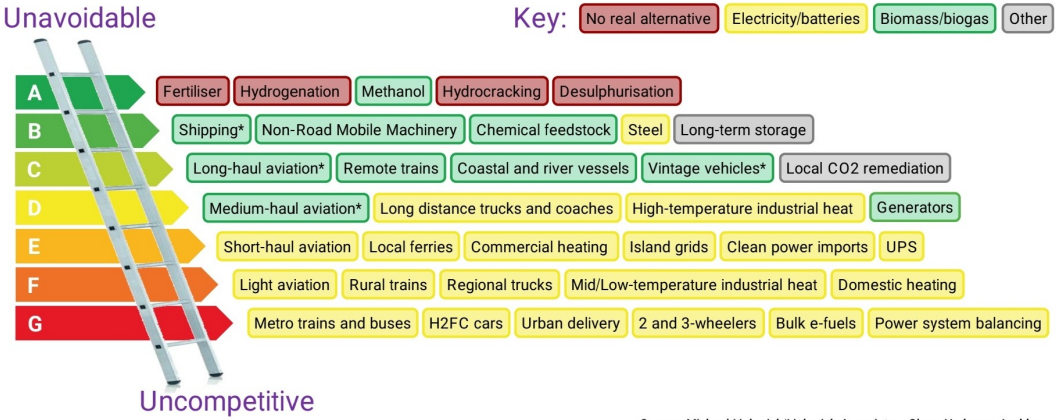
All the critical technologies for the energy transition share a small unit size, enabling fast production and installation, economies of scale in manufacturing and learning-by-doing.

- **Low-cost electricity** from wind and solar.
- **Batteries** for mobility and balancing applications.
- **Electrolytic hydrogen** (splitting water) for everything else: long-duration storage, aviation, shipping, industry.
- **Heat pumps** (missing from graphic) for building comfort and some low-temperature industry applications.

Source: Way et al, 2021

Hydrogen: the backstop of the energy transition

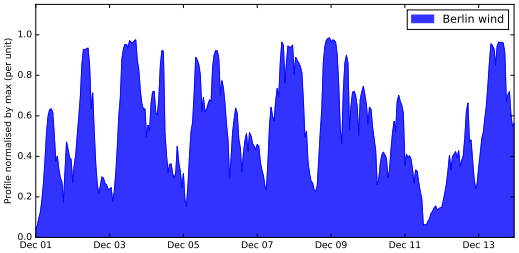
Clean hydrogen can do almost everything, but competes with direct electrification. Some say **champagne of energy transition**; could also say **backstop** for what efficiency and electrification don't reach.

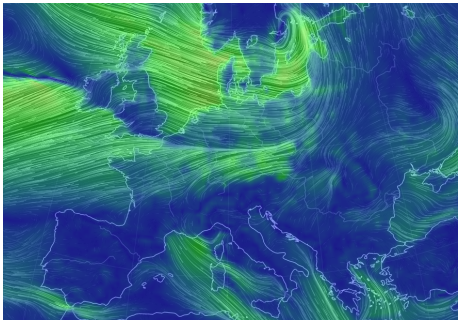


** Most likely via ammonia or e-fuel rather than H2 gas or liquid*

Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 4.1, 2021.Concept credit: Adrian Hiel, Energy Cities. CC-BY 3.0

But must take account of variability...





...and social & political constraints



Sustainability doesn't just mean taking account of environmental constraints.

There are also **social and political constraints**, particularly for transmission grid and onshore wind development.



Energy Transition: Several changes happening simultaneously

Energiewende: The Energy Transition, consists of several parts:

- Transition to an energy system with low greenhouse gas emissions
- Renewables replace fossil-fuelled generation (and nuclear in some countries)
- Increasing integration of international electricity markets
- Better integration of transmission constraints in electricity markets
- Sector coupling: heating, transport and industry electrify
- More decentralised location and ownership in the power sector