



**Energy supply,  
economics  
and transition**

**Mitigating CO<sub>2</sub>  
emissions  
and scenarios**

# 100'000 TWh annual electricity production: 4 Major options

Which can be combined ...

- a e.g. 40'000 GW of Solar and 15'000 GW of Wind (+ Hydro + Biomass +... )
- b 13'000 x 1 GW nuclear power plants
- c Carbon sequestration
- d Don't care (or too late...)
- M Revolutions: natural hydrogen / fusion

## Reminder

1GW Nuclear → 8 TWh/year (8000 hours)

1GW solar → 1-2 TWh/year (1000-2000 hours)

1GW wind → 2-4 TWh/year (2000-4000 hours)



<https://energy.economictimes.indiatimes.com/news/renewable/india-on-path-to-triple-renewable-energy-capacity-by-2030-but-faces-financing-hurdle-report/105584911>

**Carbon capture and storage (CCS)** → separation and capture of CO<sub>2</sub> from the emissions of industrial processes prior to release into the atmosphere and storage of the CO<sub>2</sub> in deep underground geologic formations

- Enables industry to continue to operate while emitting less GHGs.
- It can be applied across the energy system.
- Requirements for storage → safe, environmentally sustainable (no release) and cost-effective.
- Target policy measures and support for innovation are critical for CCS.

<https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus>

**Geologic storage:** placement of CO<sub>2</sub> into subsurface formation.

**Types:**

- Saline formations
- Oil and natural gas reservoirs
- Unmineable coal seams
- Organic-rich shales
- Basalt formations

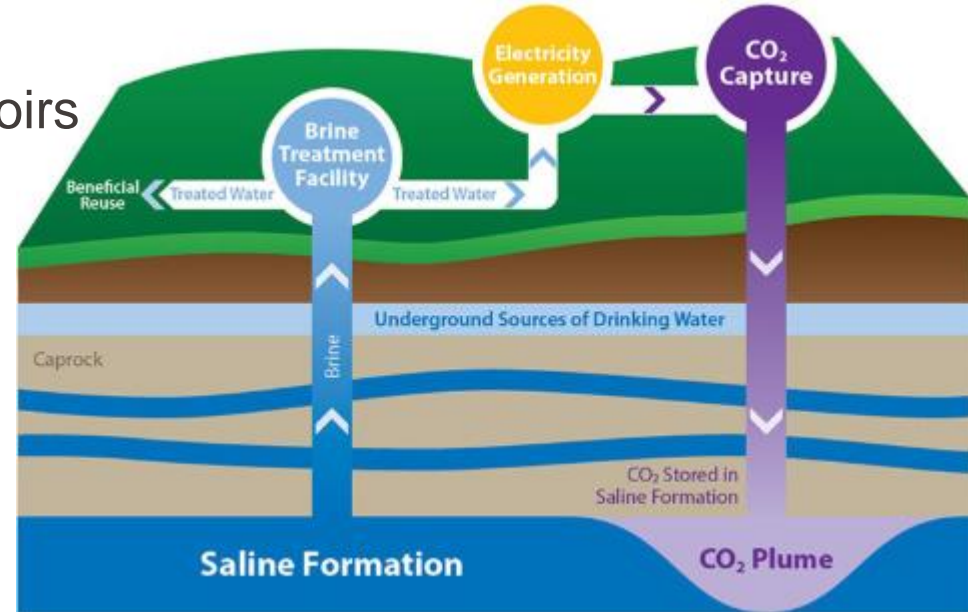
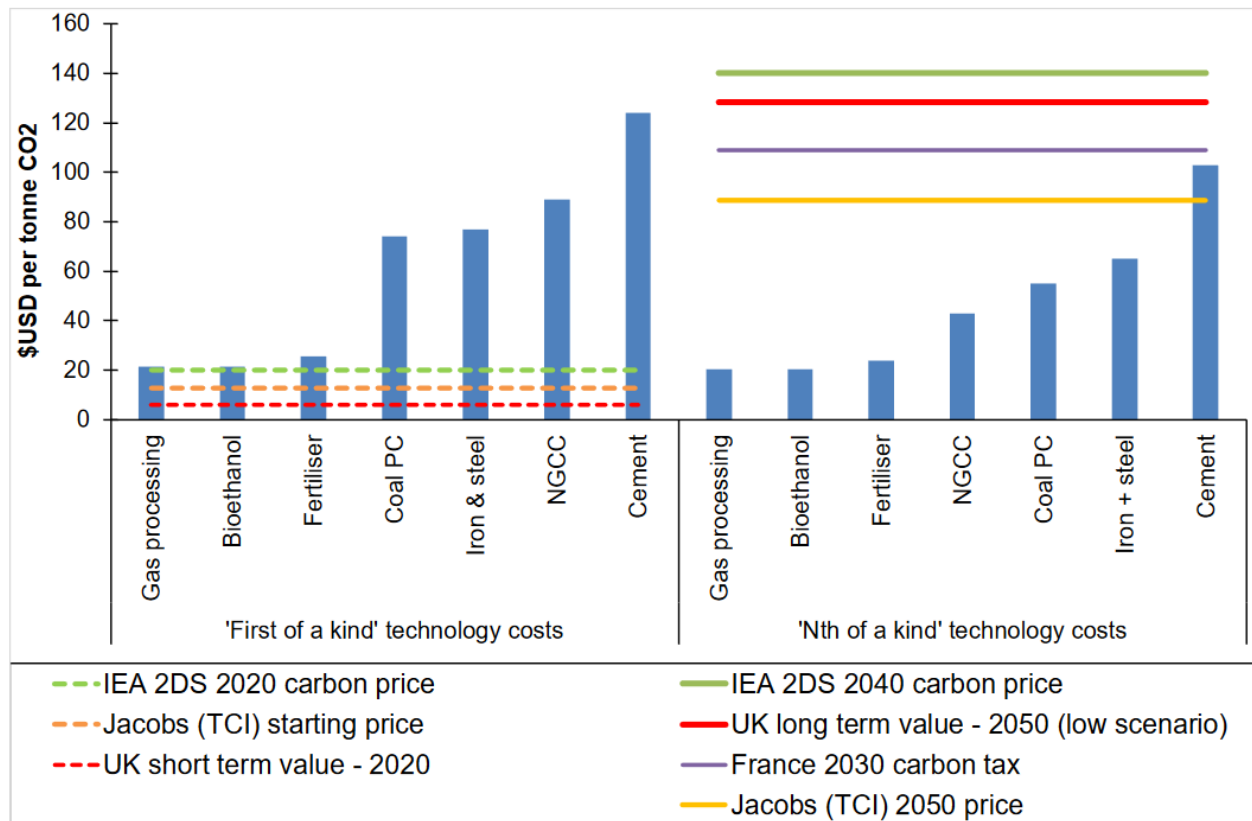


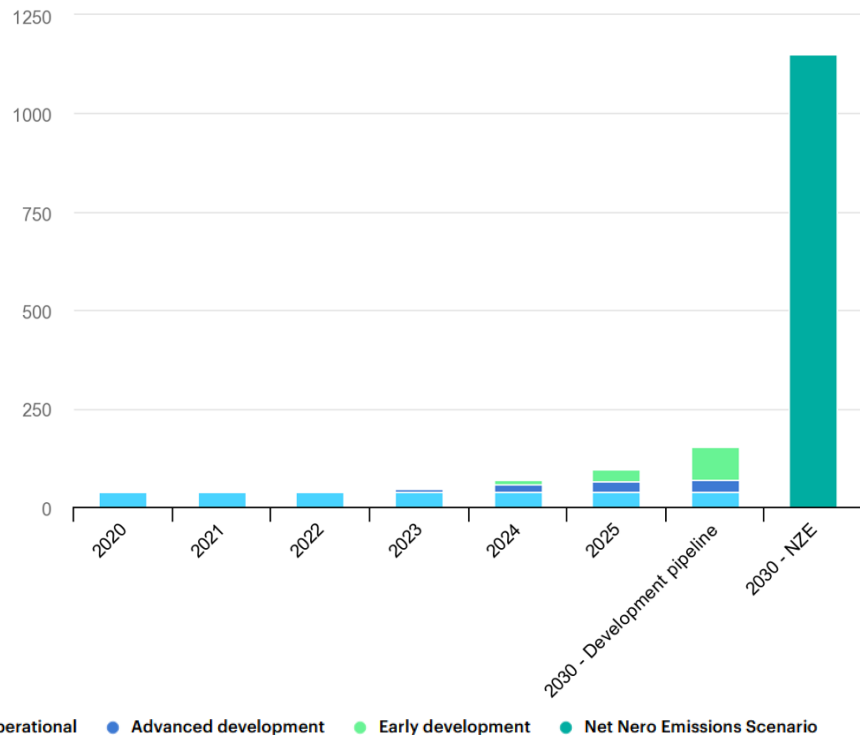
Figure 3: Reference location costs and carbon values in scenario modelling



- First large scale installation will have large investment costs: ~ 100 \$/tons CO<sub>2</sub> for coal and gas power plant (Coal PC + NGCC)
- Later projects could come down to 40 – 50 \$/tons CO<sub>2</sub> avoided

# CO<sub>2</sub> Capture and Sequestration

## Large-scale CO<sub>2</sub> capture projects in power generation in the Sustainable Development Scenario, 2000-2040



Difficult to kick-start (without high CO<sub>2</sub> taxes)

Several projects starting for cement factories (chemical reactions emits CO<sub>2</sub>)

If CO<sub>2</sub> capture costs of 100€/tons → 5 cts/kWh more for gas electricity and 10 cts/kWh for coal power plants. → in direct (loosing) competitions with renewable + storage, or nuclear

**A lot of talks and not much happening !**

<https://www.iea.org/reports/ccus-in-industry-and-transformation>



[We're On A Path To Reach  
Net-Zero Emissions -  
Pathways Alliance](#)



Canada's oil sands are on a path  
to reach net-zero emissions from  
operations.



Make oil  
production less  
dirty (around 20%  
of emission from  
extraction/processi  
ng per future  
emission when  
burning)



**Direct air capture (DAC) or direct CO<sub>2</sub> capture from the air** (e.g. Climate works, Global Thermostat....)

- needs at least 250 kWh electricity per tons of CO<sub>2</sub>
- Cost of ~ 100\$/ton claimed possible (or even 50 in 2050\*\*), right now likely more 500-600\$/tons

**Direct CO<sub>2</sub> capture from the air → will be costly for several decades**

- **Possible business for sales of CO<sub>2</sub>,**
- At 100\$/ton → cost of carbon in 1 m<sup>3</sup> of CH<sub>4</sub> (power to gas) → 0.27\$/m<sup>3</sup> (n.b. current price of gas)

**Open question: should we however work on DAC?**

- Less costly to substitute fossil with renewables.
- Less costly in volume to make CSS from Coal/gas powerplants ?
- Or prepare the world for massive DAC when system is decarbonised ? (likely yes to contain/reverse climate change)



[\\*\\*Techno-economic assessment of CO<sub>2</sub> direct air capture plants, Fasihi et al. 2019](#)



# CO<sub>2</sub> Capture and Sequestration – Land Use, Land-Use Change and Forestry (LULUCF)

## Biological carbon sequestration

- Plants absorb CO<sub>2</sub> from the atmosphere and store some as aboveground and belowground biomass.
- Soil and dead organic matter/litter can also store some CO<sub>2</sub>, e.g. in Peatlands.
- In US (since 1990) LULUCF activities have resulted in more removal CO<sub>2</sub> than emissions.
- In countries when deforestation happens, the effect is opposite.

# CO<sub>2</sub> Capture and Sequestration – Land Use, Land-Use Change and Forestry (LULUCF)

Enhance carbon pools to reduce emissions and increase potential to sequester carbon from atmosphere.

## Possible actions

- Change in Uses of Land:
  - Increase carbon storage by using land differently.
  - Maintain carbon storage by avoiding land degradation.
- Change in Land Management Practices:
  - Improve management practices on existing land-use types (plant after human-induced disturbances to accelerate vegetation growth, reforestation).

## Tree planting 'has mind-blowing potential' to tackle climate crisis



- Worldwide planting programme
  - Additional 0.9 billion ha (to the existing 4.4 billion ha) of forest could store 205 Gt of Carbon (=  $3.65 \times 205 = 750$  Gt of CO<sub>2</sub> = 17 years of emission at current rate)
- Crop fields and urban areas are not considered.
- Reforestation could take 50-100 years to remove 750 Gt of CO<sub>2</sub>
- **Advantages:**
  - Available for starting now.
  - Cheap solution (?).
  - Individuals could make impact by growing trees themselves.

"The global tree restoration potential", Jean-Francois Bastin et al., Science 65 (Jul 2019), 76-79

<https://www.theguardian.com/environment/2019/jul/04/planting-billions-trees-best-tackle-climate-crisis-scientists-canopy-emissions>

## Planting trees can support the world in mitigating climate change

- But potential likely overestimated (see discussion in <https://science.sciencemag.org/content/366/6463/317> )
- Planting trees is one aspect (nice communication) growing them is more difficult and many challenging projects with dying trees. Risks of fire also increase with global warming
- It will only slow down planet warming, as it takes years to act
- **It can be a quite low cost approach (20 to 40\$/tonnes). Can easily be scale up**

### Other approaches include (e.g.)

- Creation of Bio-char or Charcoal (by slow pyrolysis) and integration to ground
- e.g. with bamboos (fast growth)
- Potential in x Gt per year (up to 12% according to some scientists)



Woolf, Dominic et al "Sustainable biochar to mitigate global climate change". Nature Communications. 1 (5): (2010) 1–9.

- Better insulated and designed house (can save up to 2/3 of energy)
- Better control of hidden consumptions (pumps, ventilation, potential for > 30% saving in CH, close to 12 TWh per year)
- Energy saving bulb, appliances (90% to 30% saving),
- Use electricity instead of fuels to power engines (gain a factor 3\* )
- Use electricity and heat pumps to extract heat (gain a factor 3\* to 5)
- Build with materials that embeds CO<sub>2</sub>, (instead of emitting) eg. Wood, and replant !

\*But almost similar according to the BP method in terms of primary energy

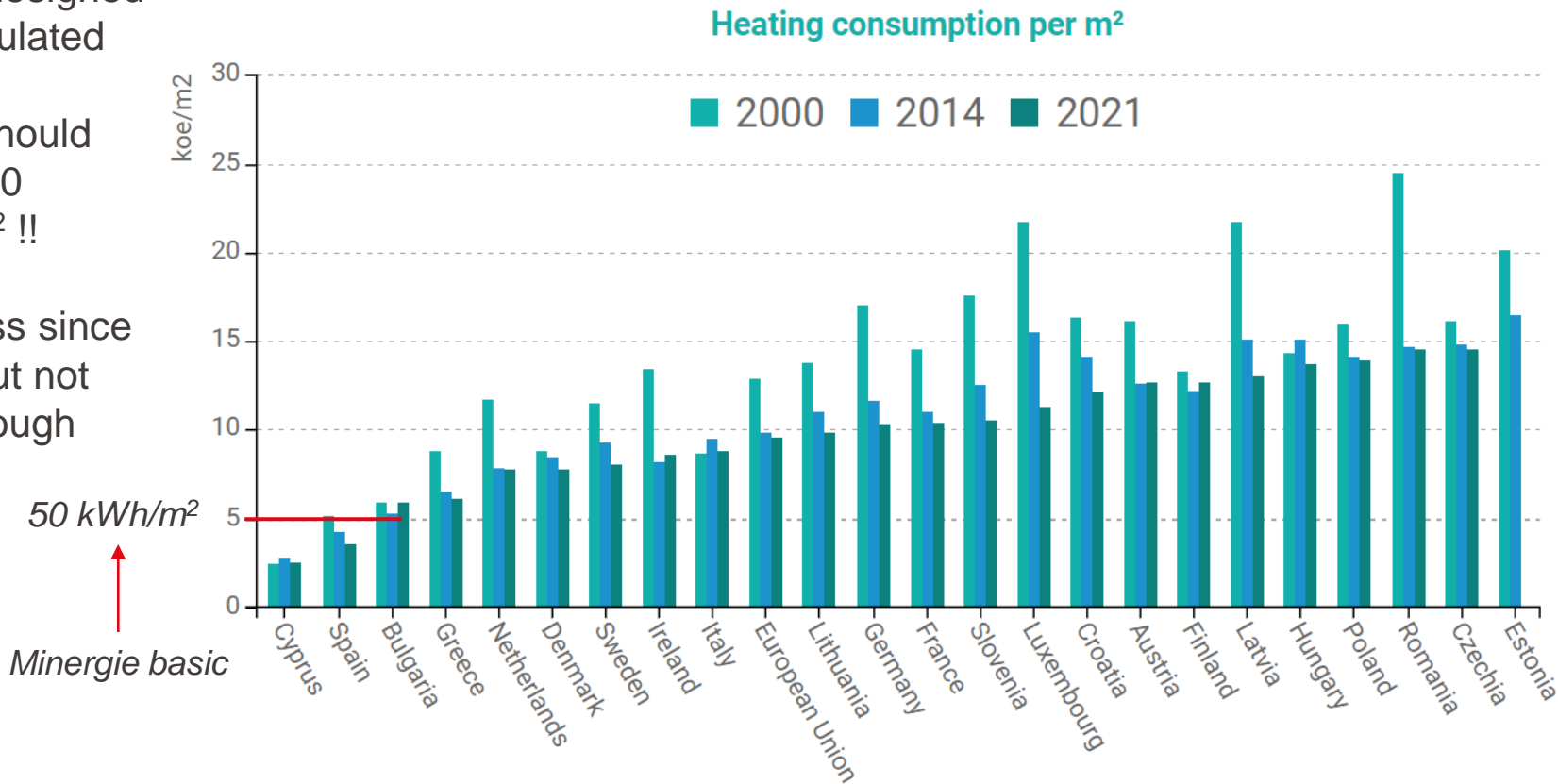
Wood construction, up to 30 floors..  
See work by M. Green, Architect



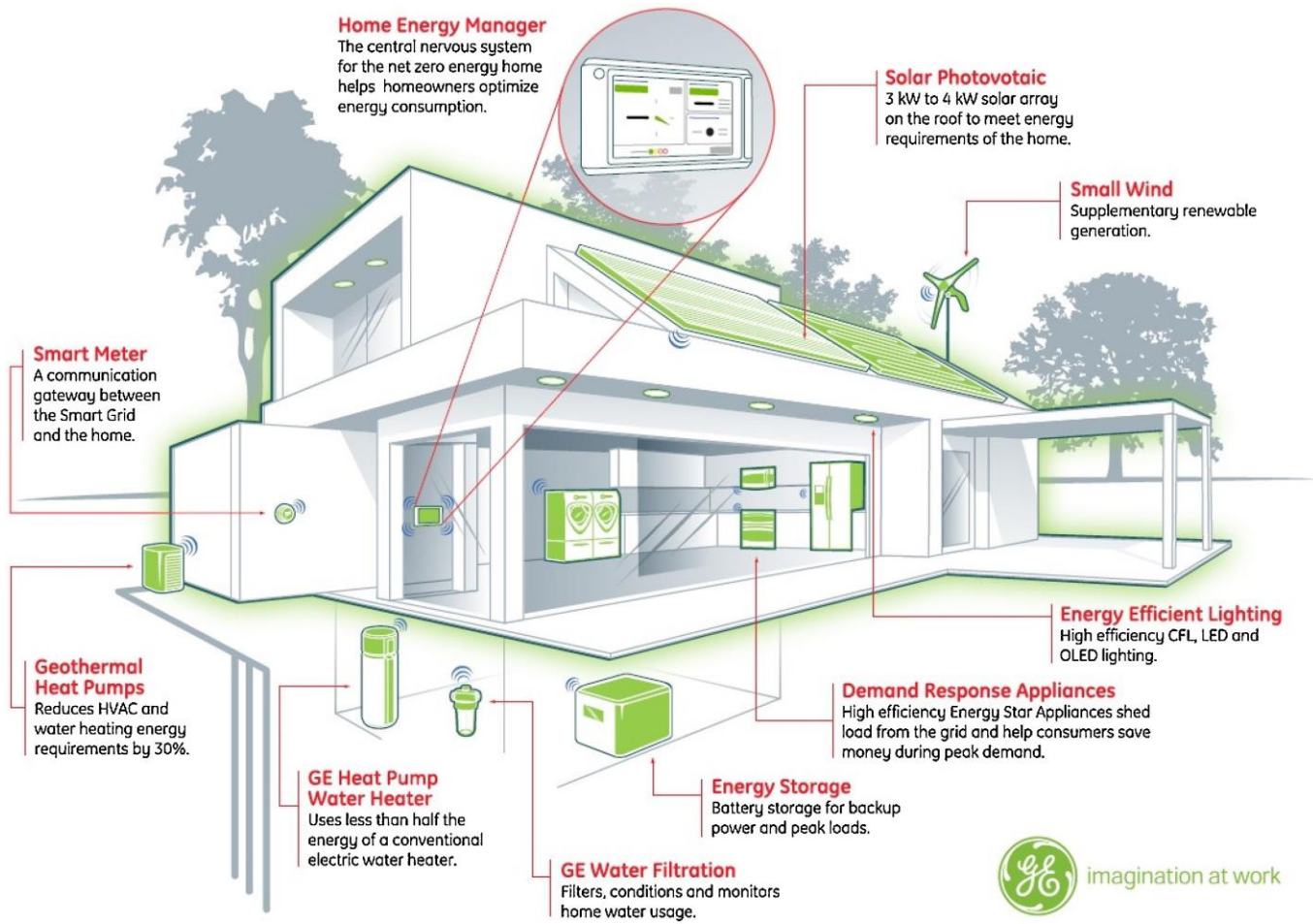
# Building: trend to heating needs in Europe

A well designed and insulated home could/should reach 50 kWh/m<sup>2</sup> !!

Progress since 2000 but not fast enough



# Net zero energy buildings



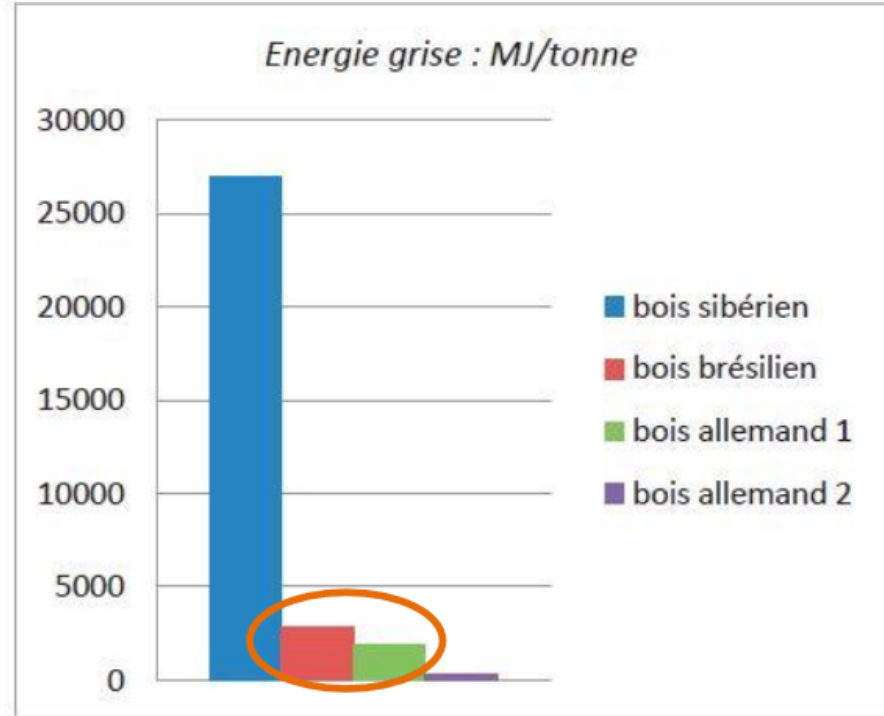


# Wood as a future (and past) building material

- Build with materials that embed CO<sub>2</sub> (instead of emitting), e.g. wood.
- For a building in Oslo → Brazilian wood comparable to German wood.
- Pay attention to both the travel distance and the transport model (sometimes disput methodology)



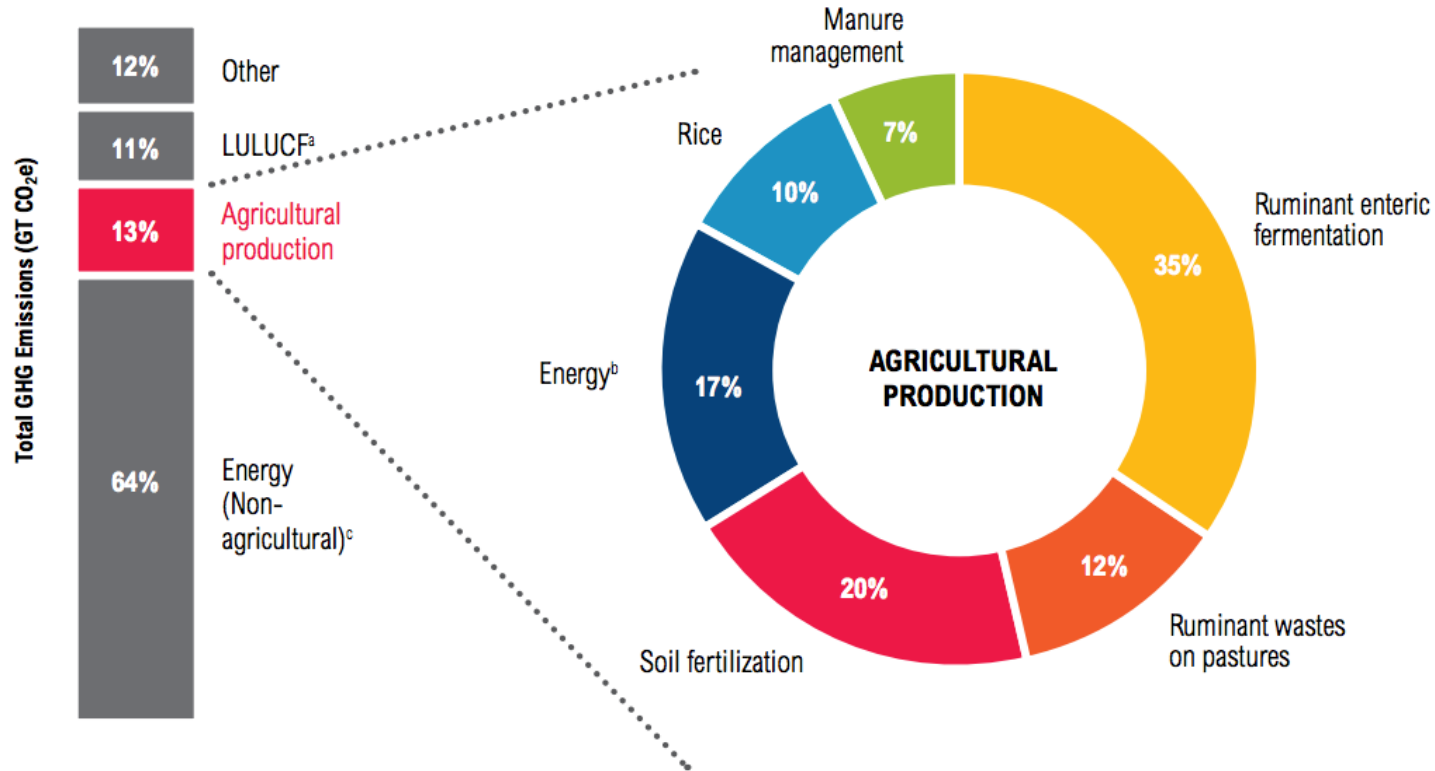
Mjøsa Tower in Brumunddal near Oslo, Norway  
85.4 metres world's tallest wooden building.



- Siberian wood : 10 000 km by road (truck)
- Brazilian wood : 10 000 km by sea (90 %) and road (10 %)
- German wood : 500 km by road (truck)
- German wood : 500km by train

## Sources of GHG emissions:

- emissions of  $N_2O$ .
  - Application of Management practices on soils increase availability of nitrogen in the soil (50% emissions) → synthetic and organic fertilizers.
  - Growth of nitrogen-fixing crops.
  - Drainage of organic soil.
  - Irrigation practices
- Livestock (cattle) (~30% emissions) → production of  $CH_4$  from digestive processes, up to 12-15% of  $CO_2$  eq emissions worldwide
- Management manure from livestock →  $CH_4$  and  $N_2O$  emissions.
- $CH_4$  from rice cultivation (and  $N_2O$ )... 10% of global methane emission
- Smaller sources:
  - $CO_2$  from liming and urea application.
  - $CH_4$  and  $N_2O$  from burning crop residues

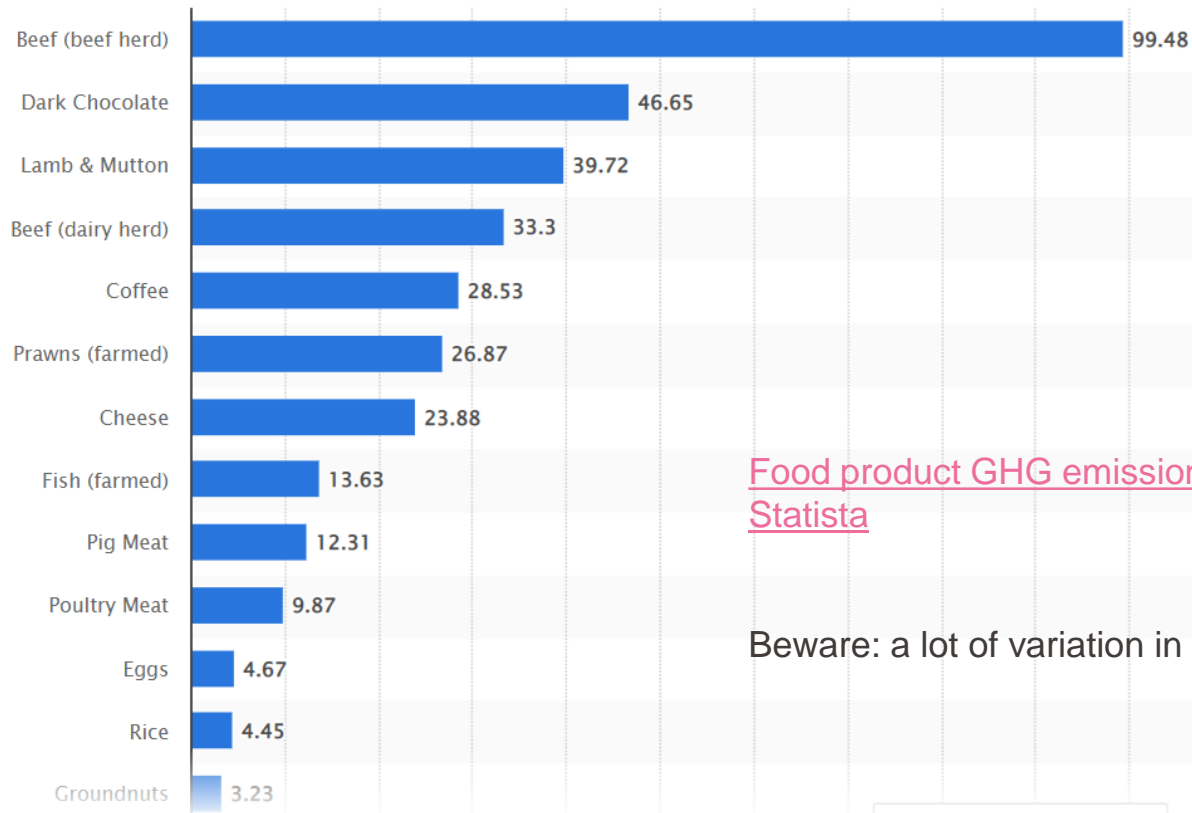


LULUCF: Land Use, Land-Use Change and Forestry

2009

<https://skepticalscience.com/animal-agriculture-meat-global-warming.htm>

# Average greenhouse gas emissions per kilogram of major food products worldwide

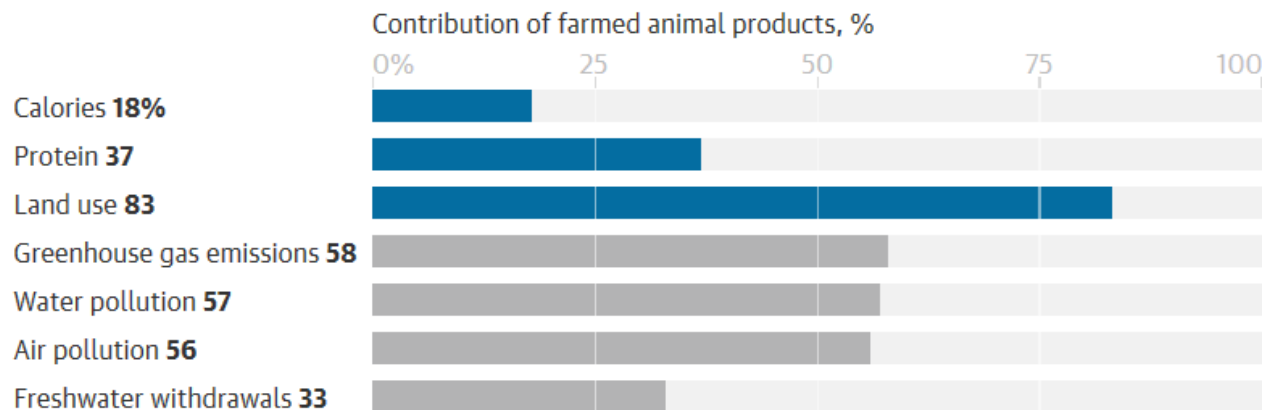


[Food product GHG emissions per kilogram worldwide | Statista](#)

Beware: a lot of variation in the data !

- **Vegan diet** → best way to reduce impact on GHG, global acidification, eutrophication, land use and water use.
- Without meat and dairy consumption, global farmland use could be reduced by > 75%.

**More than 80% of farmland is used for livestock but it produces just 18% of food calories and 37% of protein**



## Courses of action for reduction of emissions:

- Land and crop management → adjust methods for managing land and growing crops.
- Livestock management → adjust feeding practices and other issues to reduce  $\text{CH}_4$  emissions (and reduce livestock)
- Manure management:
  - control the decomposition of manure to reduce  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions.
  - Capture  $\text{CH}_4$  from manure decomposition to produce renewable energy.

1. What is the economic sector that contributes more to the GHG emissions?
  - a) Aviation
  - b) Electricity and heat production.
  - c) Agriculture, forestry and other land use.
  
2. Will planting trees mitigate strongly the CO<sub>2</sub> emissions in the atmosphere?
  - a) Yes.
  - b) No.
  - c) It could but it would take long and a huge effort ...
  
3. In agriculture, the CO<sub>2</sub> emission go from largest to lowest:
  - a) Beef, farmed fish and tofu.
  - b) Poultry, beef and nuts.
  - c) Beef, tofu and poultry.



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**Consumption can be decreased, human can be more reasonable but Energy will still be needed !**

**→ Development of renewables:**

**Challenges:**

1. Policy and regulatory uncertainty.
2. High investment risks in developing countries.
3. System integration of wind and solar.
4. (Lobbies and Trump and CO)

**Source of additional potential:**

1. Solar PV.
2. Onshore/Offshore wind.
3. Hydropower, biomass, geothermal

# Somes scenario for the future

- To differentiate between models «what should be done», and scenarios «what will likely happen»
- Scenarios/models based on announed policies by country
- Levels of details of analysis or simulation/optimisation very different
- Of course strongly diverging numbers depending on the sources
- Often cost perspectives and learning curves not integrated (e.g. for renewable and electricity storage)

E.g. a simple tool to start



<https://www.energyscope.ch/fr/>

Note: in the last session we'll have a guest who will present one scenario/model based for Switzerland

[En-ROADS \(climateinteractive.org\)](https://climateinteractive.org/)

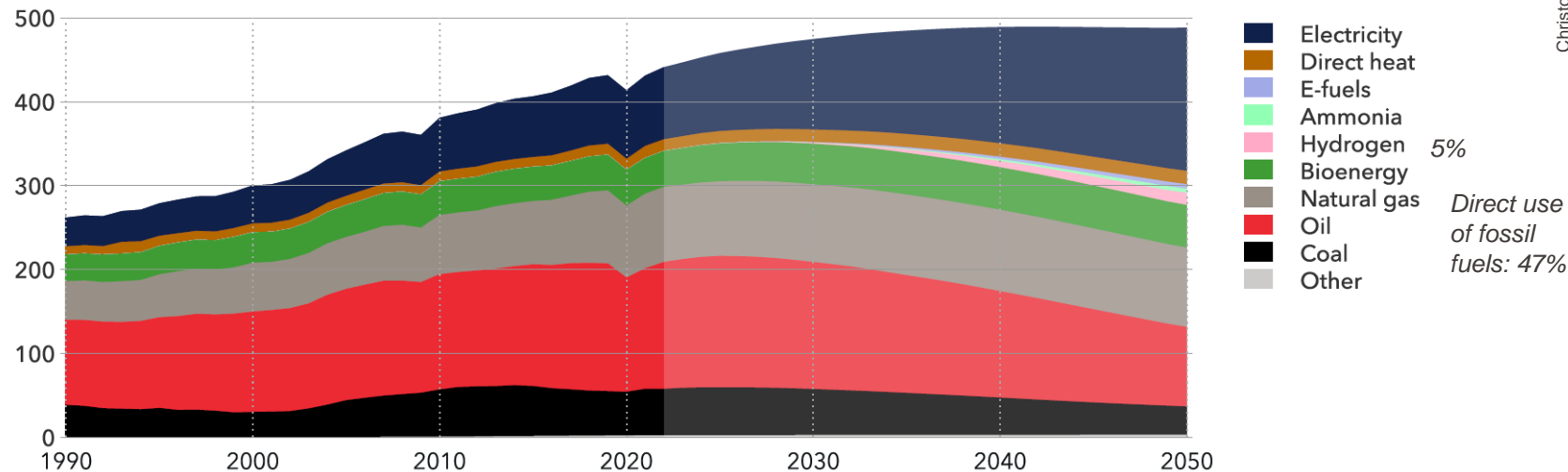
# World final energy demand by : one scenario, still keeping a lot of fossile by DNV

*! Use The Physical Energy Content Method (IEA reports).  
kWh from wind, solar and hydro, and thermal kWh for nuclear and bioenergy*

FIGURE 1.29

## World final energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2023)

Source: Energy Transition Outlook, [DNV.com](https://www.dnv.com) - When trust matters - DNV

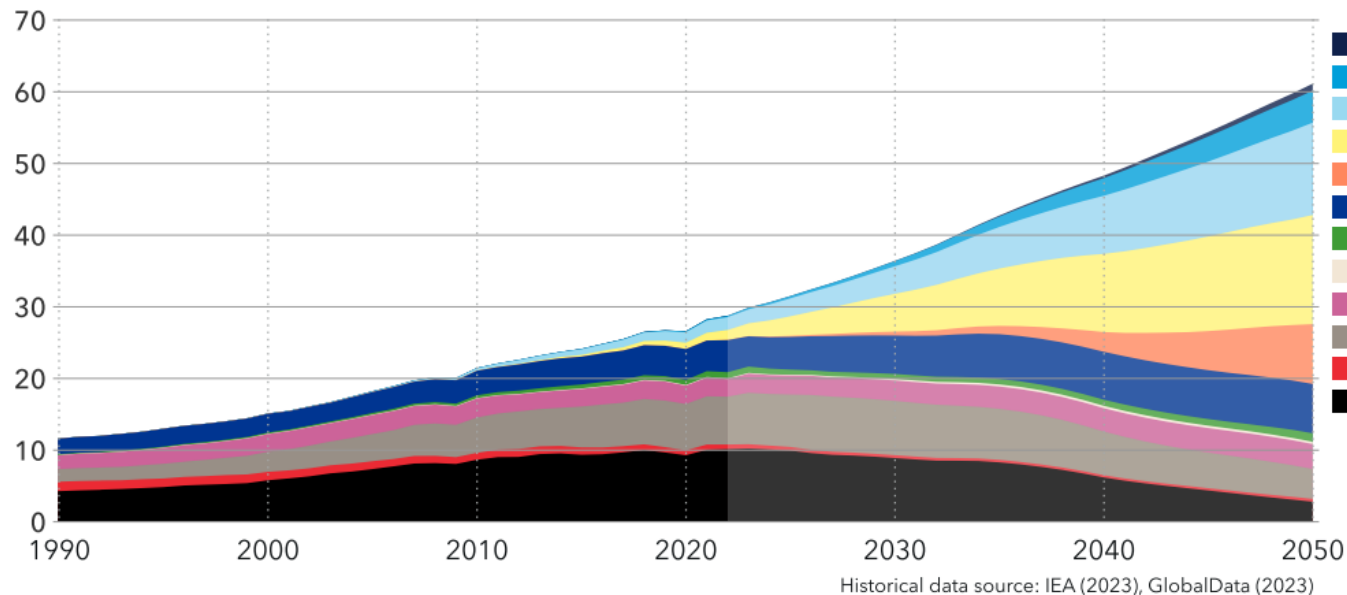
# The same scenario for the power sector

## 57'000 TWh

FIGURE 2.4

### World grid-connected electricity generation by power station type

Units: PWh/yr



Renewable Energies by 2050: 82%  
Solar + Wind = 69%

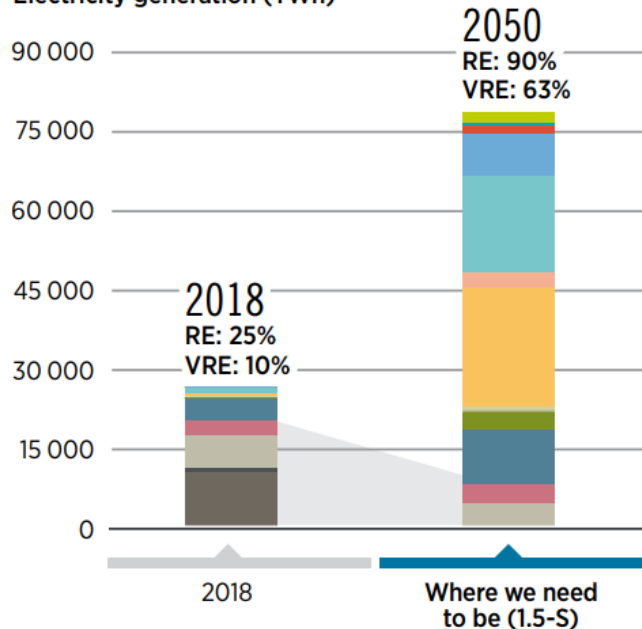
30%

# EPFL Renewable Energies – Potential (2050), 1.5°C scenario

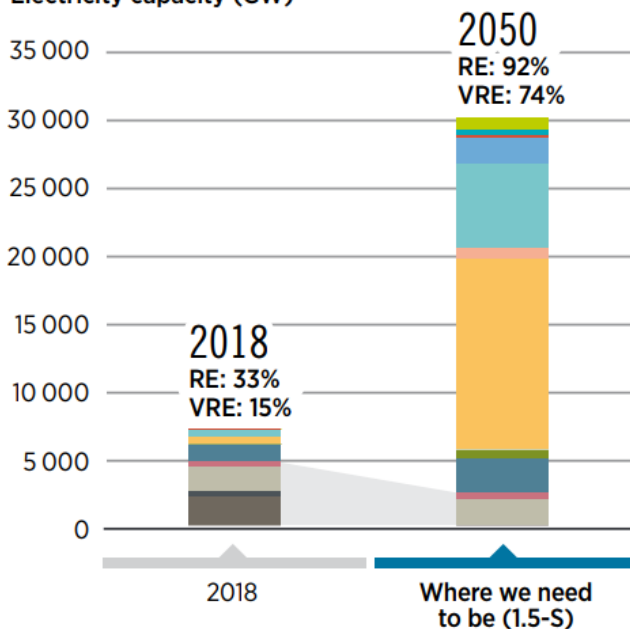
30

Claudia Binder

Electricity generation (TWh)



Electricity capacity (GW)

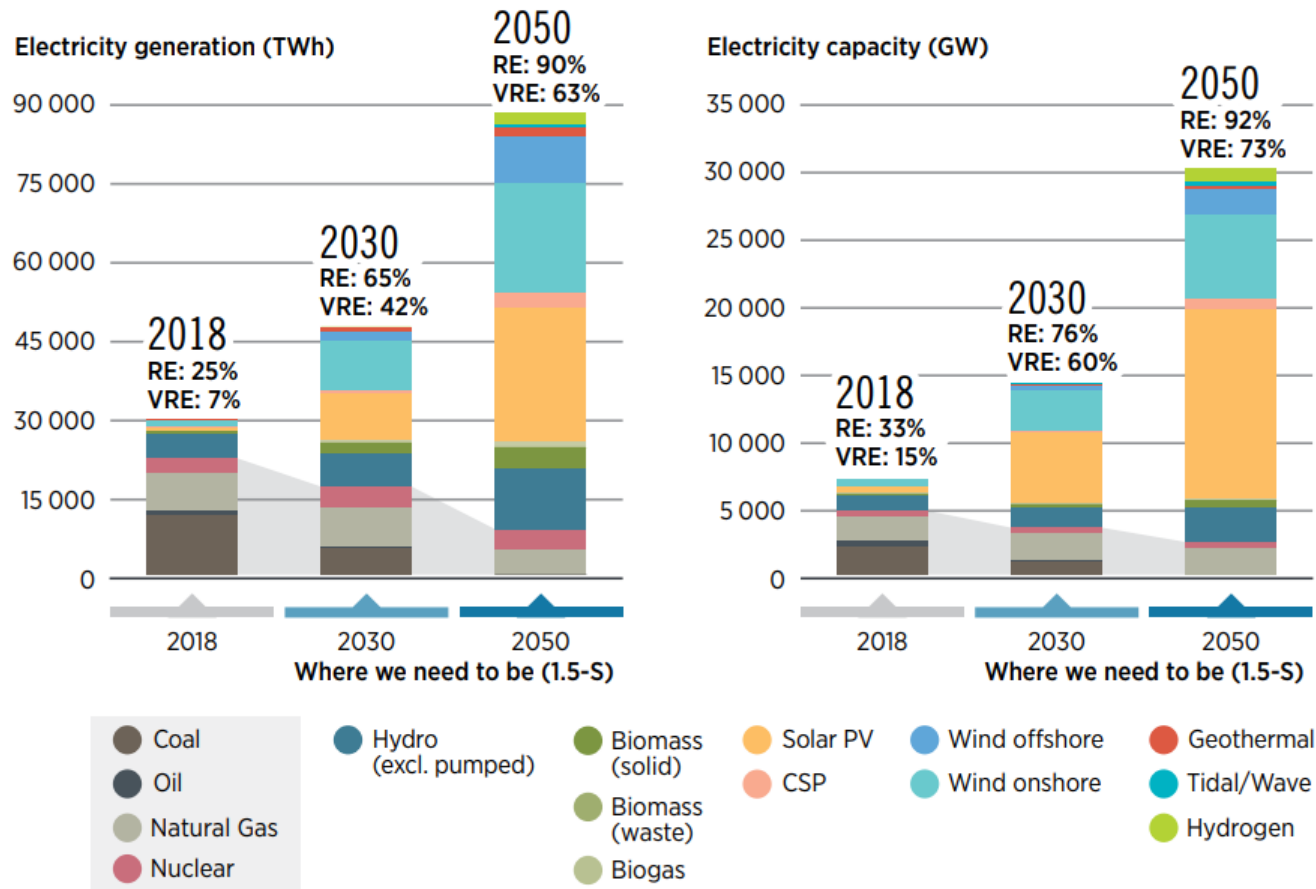


## IRENA 2021

Tech 2050	Electricity generation [TWh]	Share [%]
Wind	25'000	31
Solar PV	25'000	31
Hydro	10'000	13
Bioenergy	5'000	6
Geothermal	2'000	3
Others	5'000	6
<b>Total</b>	<b>72'000</b>	<b>90</b>

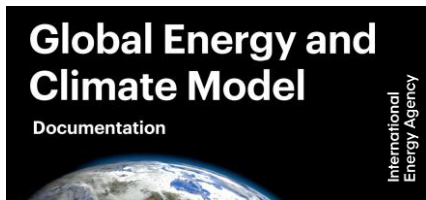
Positive/should be scenario  
But still some TWh missing  
(30'000 ?)

**FIGURE 2.3** Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050



**IRENA 2022**  
**13'000 TWh**  
**added...**  
**still some gas**





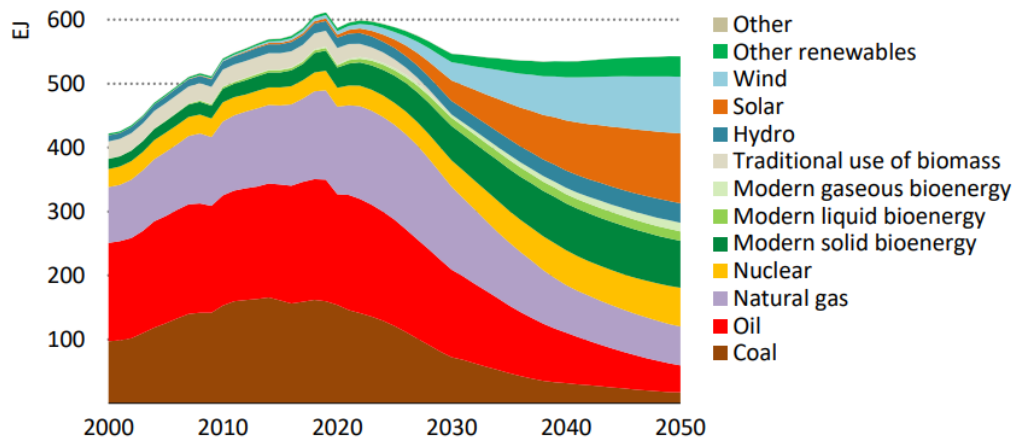
[Global Energy and Climate Model Documentation \(windows.net\)](#)



[Net Zero by 2050 - A Roadmap for the Global Energy Sector \(windows.net\)](#)

**Figure 2.5** ▶ Total energy supply in the NZE

(net zero emission)



IEA. All rights reserved.

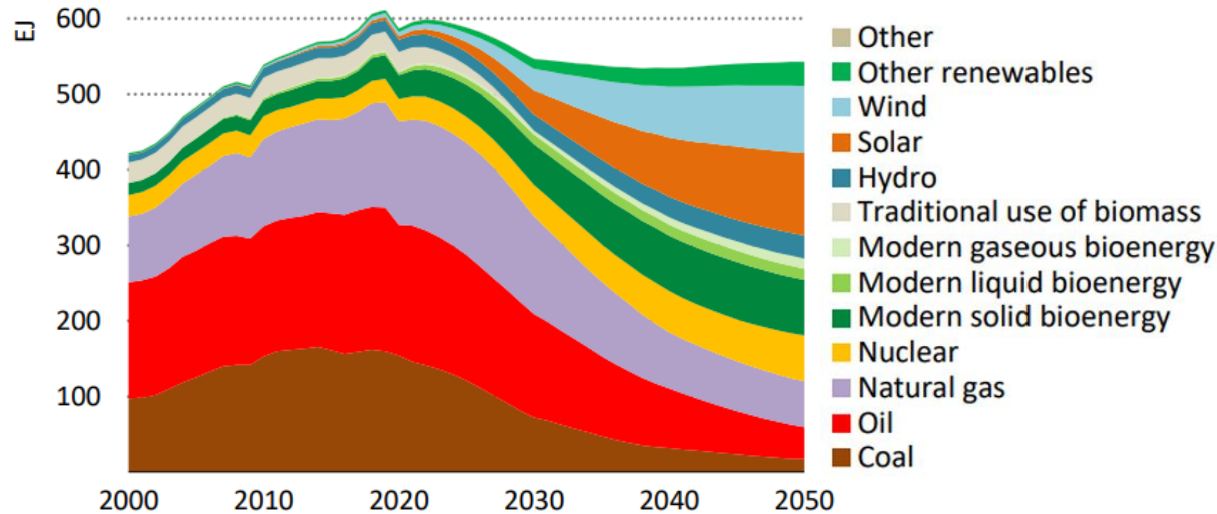
*Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050*

The **2021 NZE** scenario of IEA also relies on new renewable. But it also bets **on carbon sequestration to compensate for fossiles emissions**, and a significant amount of bioenergy.

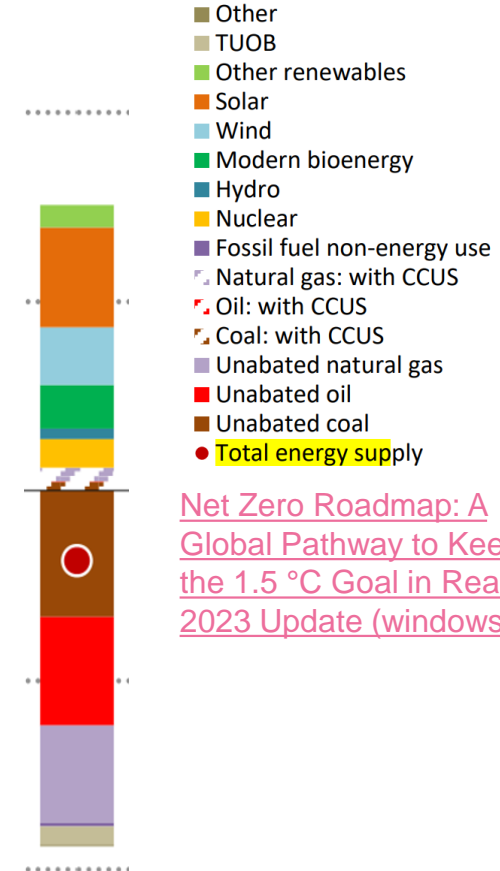
Note on IEA data: kWh of wind, hydro solar counted directly (not muliplied by 2.5 as in BP reports). The thermal kWh for all thermal source counted as such (including for nuclear x3 ). The NZE 2021 would mean around 30'000 TWh solar, 27'000 TWh wind by 2050, Nuclear ~ 4300 TWh (from 2700 today)

**Figure 2.5** ▶ Total energy supply in the NZE

2021 scenario

**2023 scenario:** changes compared to today

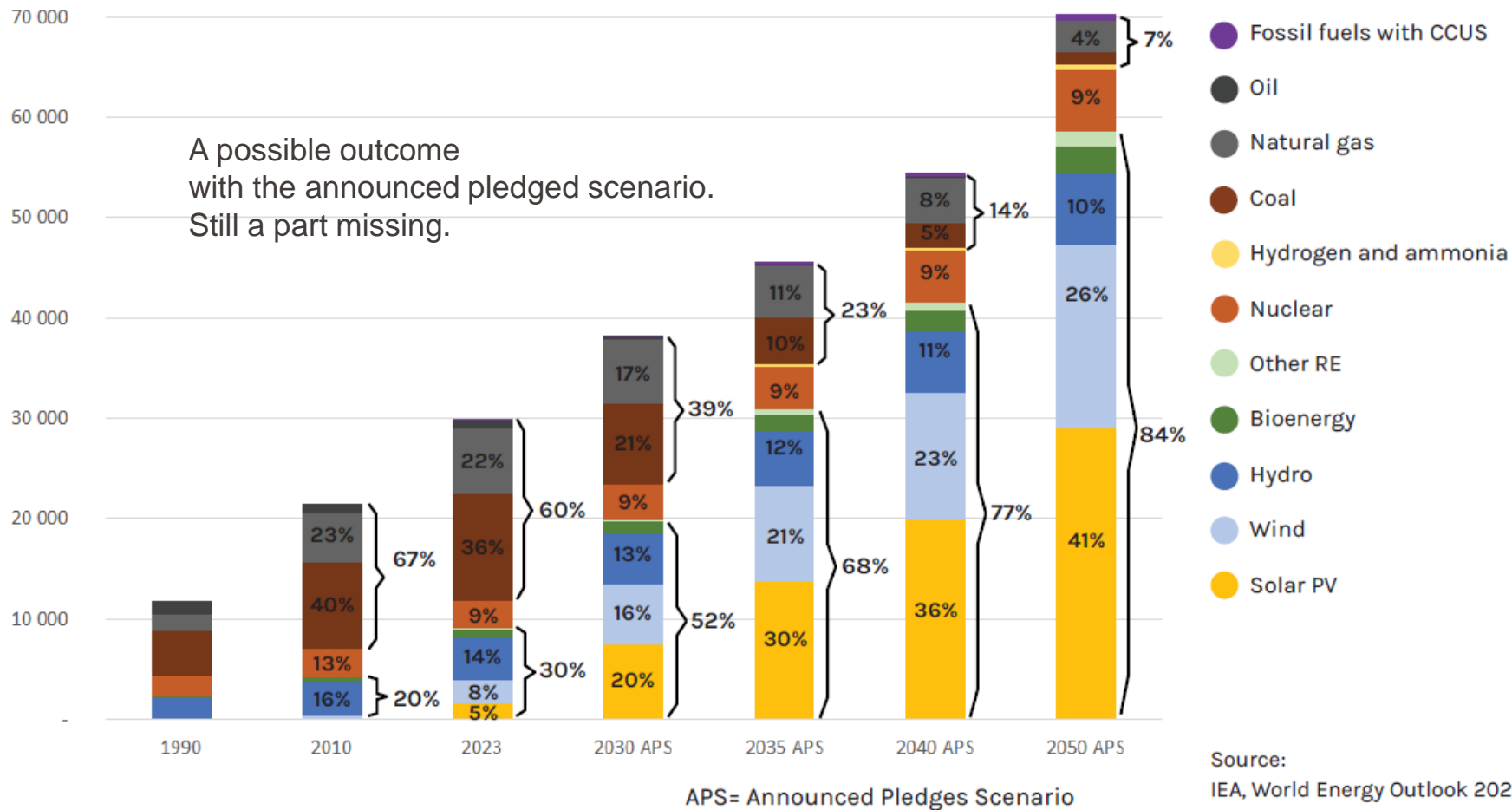
IEA. All rights reserved.



[Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update \(windows.net\)](#)

The 2023 Net zero scenario of IEA sees much less carbon sequestration and much more solar, and more nuclear.  
almost 30% increase in PV compared to 2021 scenario → around 39'000 TWh PV, 25'000 TWh wind,.....

# World Electricity Generation 1990 - 2050



Courtesy ANF

**A cautious note:  
all IEA, IPCC proposed scenario are slow and even  
IRENA scenario are not ambitious enough for  
decarbonisation. But they improve over the years....**

## **A major points in those scenarios**

- systemic overevaluation of the costs of new renewables (e.g. IPCC with PV powerplants at 1€/W in 2050 leading to low amount of solar)
- overestimation of the costs required for changes.

*“They explained that the economic potential of solar and renewables keep being largely underestimated while energy transformation and mitigation costs, by contrast, are being overestimated”*

[www.pv-magazine.com/2021/03/31/solar-still-largely-underestimated/](http://www.pv-magazine.com/2021/03/31/solar-still-largely-underestimated/) and e.g. the cited reference in Joule: [Solar photovoltaics is ready to power a sustainable future](#)

# Towards full system modelling

# Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe

## A B S T R A C T

Two transition pathways towards a 100% renewable energy (RE) power sector by 2050 are simulated for Europe using the LUT Energy System Transition model. The first is a Regions scenario, whereby regions are modelled independently, and the second is an Area scenario, which has transmission interconnections between regions. Modelling is performed in hourly resolution for 5-year time intervals, from 2015 to 2050, and considers current capacities and ages of power plants, as well as projected increases in future electricity demands. Results of the optimisation suggest that the levelised cost of electricity could fall from the current 69 €/MWh to 56 €/MWh in the Regions scenario and 51 €/MWh in the Area scenario through the adoption of low cost, flexible RE generation and energy storage. Further savings can result from increasing transmission interconnections by a factor of approximately four. This suggests that there is merit in further development of a European Energy Union, one that provides clear governance at a European level, but allows for development that is appropriate for regional contexts. This is the essence of a SuperSmart approach. A 100% RE energy system for Europe is economically competitive, technologically feasible, and consistent with targets of the Paris Agreement.

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# Modelling at all country level the Power Sector for full transition

## Considerations:

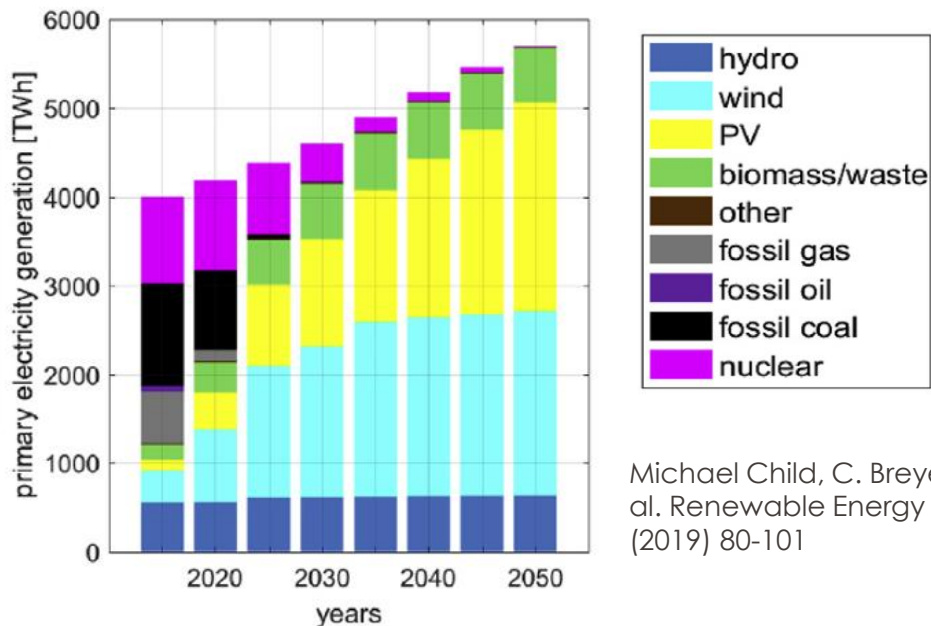
- Hourly rate electricity generation and demand in (partially) decarbonized scenario.
- New interconnection lines (Including HVDC).
- Consider Region and Area solutions (more interconnected)
- Biomethane and synthetic methane replace fuels when required
- Increase role of batteries for energy balancing by 2025.
- Learning curve for cost of PV, wind and batteries

[See paper : Low-cost renewable electricity as the key driver of the global energy transition towards sustainability – ScienceDirect](#)

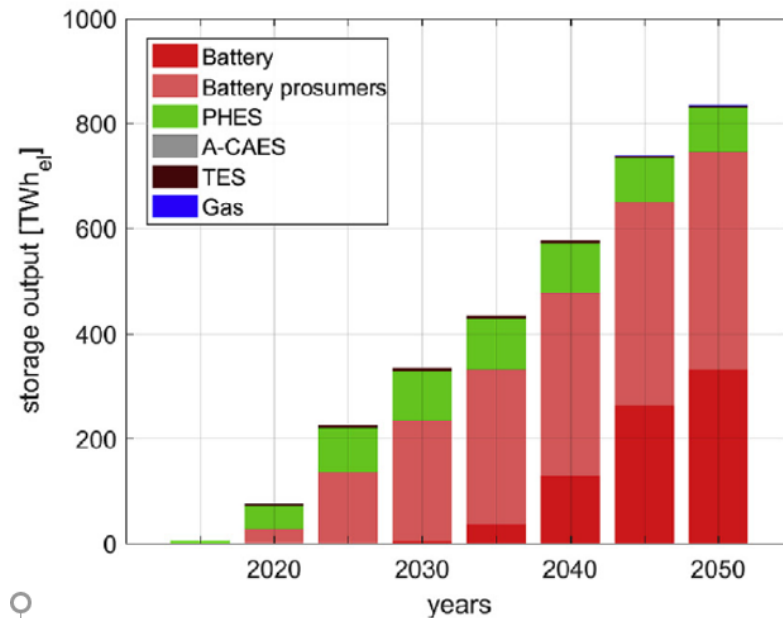


# A short look at Europe: a first partial decarbonisation

In a area connected scenario for clean power sector (with only moderate electrification) \*\*

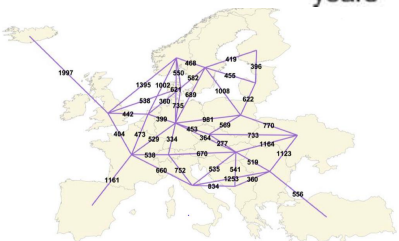


Michael Child, C. Breyer, et al. Renewable Energy 139 (2019) 80-101



Battery storage and pumped hydro necessary to balance the grid on hourly bases → **Overall cheaper cost per kWh (6-7 cts/kWh)**

In Europe: good complementarity between wind and sun on a monthly base. System stable on an hourly base thanks to storage



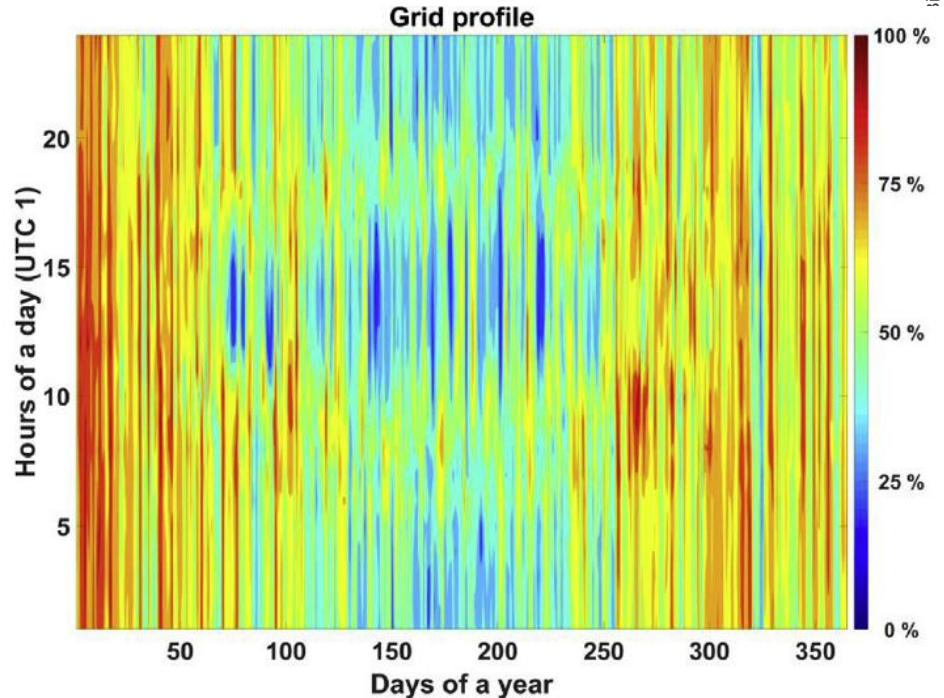
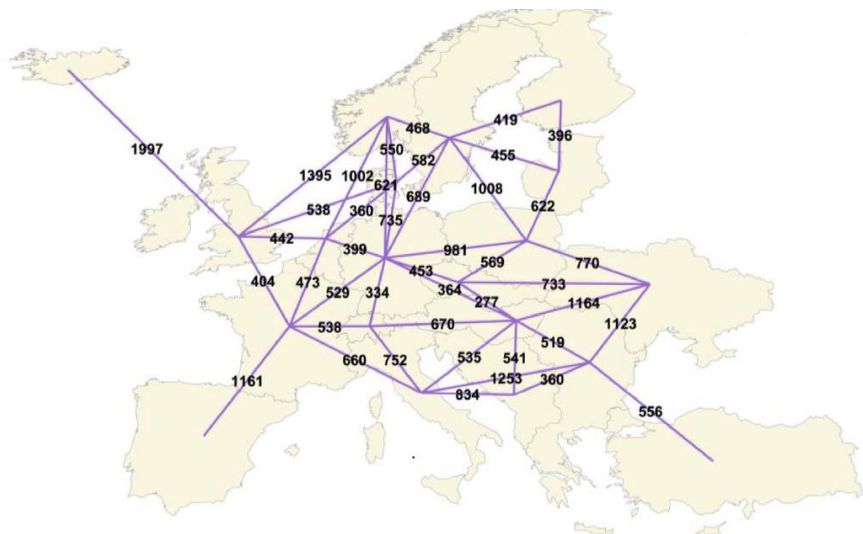


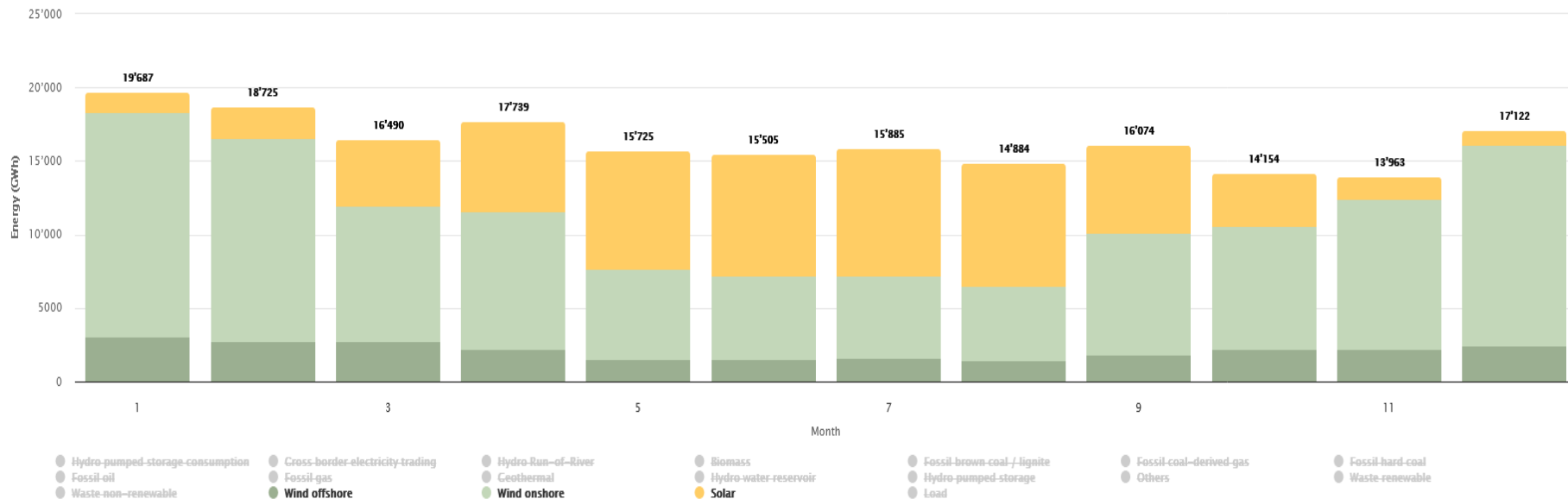
Fig. 14. Grid utilisation profile for the Area scenario in 2050.

# Exemple of complementarity wind-solar

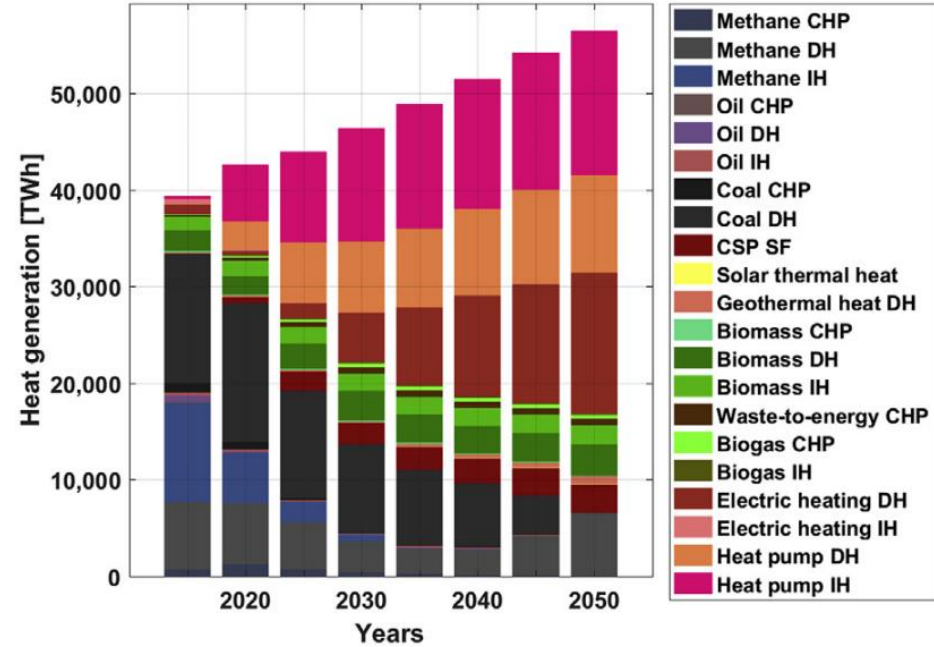
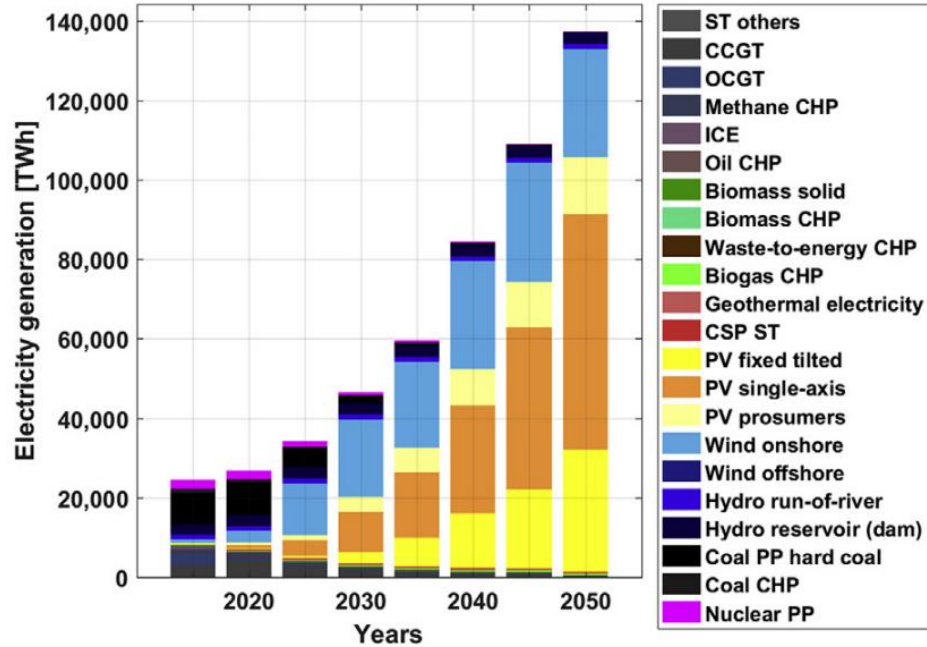
Wind vs. PV : a good complementarity winter-summer in Europe, CH, and germany

Electricity generation from wind and solar PV in Germany in 2024.

*Chart by Fraunhofer ISE, 2024.*



# A complete world scenario with 134'000 TWh electricity<sup>42</sup>



Low-cost renewable electricity as the key driver of the global energy transition towards sustainability - ScienceDirect

<https://doi.org/10.1016/j.energy.2021.120467>

■ Bodganov, Breyer et al.

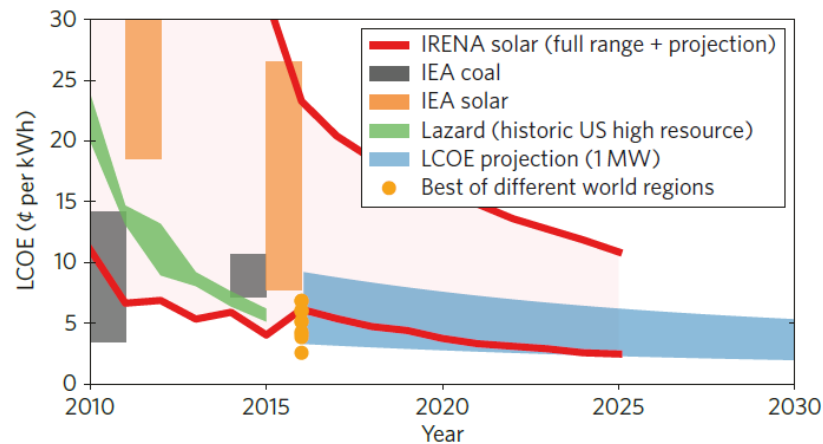
Because of its low LCOE,  
PV tends to grow in share in such scenario with  
**63'000 GW (needs more than 2 TW per year)**  
which reserves spaces for Power-to-gas

# General Literature to the Feasability of 100% Renewable Systems (more than sector)

Several studies show the feasibility. They answer to those who say it is not possible.  
Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems' T.W. Brown, et al. Renewable and Sustainable Energy Reviews 92 (2018) 834–847

**Note:** many scenarios underestimate the potential and potential low cost of Wind, PV\*\*, and batteries.

For example: breyer et al. of Lappeenranta University of Technology, make aggressive but possible assumptions (e.g. 0.3€/W for PV power plants).  
People enclined against renewable takes worst case (e.g. 1.5€/W for PV power by Jancovici)

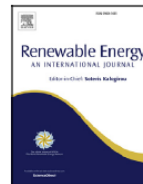


Overestimated costs of solar by IEA reports.



Contents lists available at ScienceDirect

## Renewable Energy

journal homepage: [www.elsevier.com/locate/renene](http://www.elsevier.com/locate/renene)

Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage

Mark Z. Jacobson<sup>\*</sup>, Anna-Katharina von Krauland, Stephen J. Coughlin, Frances C. Palmer, Miles M. Smith

*Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, 94305-4020, USA*



Possible even  
in US !

(but note:author  
is seen  
controversial  
controversial)

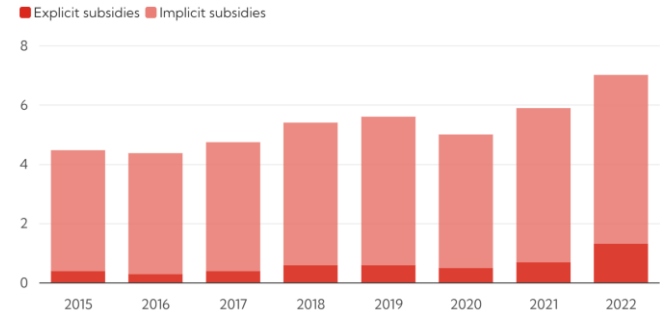
# How much does the energy transition costs ?

- IRENA (international renewable energy agency) gives high estimates: investments/costs up to **3.8 Trillions/year** (typically 3-4% of world GDP) (2022).
- **Strong improvement in components costs including battery costs will make the bill lower** (e.g. less grid adaptation). Renewables (and batteries) are always underestimated in their capacity to decrease their pricing.
- Important parts in buildings and grids, a small part in storage (even though trade-off not always obvious), which might change with the lower cost of storage

**Direct costs are not small for a full transition but they are more than bearable or even “cheap” if you consider:**

- No more fossil fuel import (CH 6-8 billions/years in CH and continues after 30 years) and fossil fuel subsidies
- Reduced dependency on fluctuating price for consumers
- Improved health, more jobs
- Reduced global warming : a huge price

**Fossil fuel subsidies topped \$7 trillion last year**  
(total fossil fuel subsidies, trillions of USD)



Source: IMF staff calculations.

Note: Figures from 2019 onwards use projections for fuel use. Explicit subsidies: undercharging for supply costs. Implicit subsidies: undercharging for environmental costs and forgone consumption taxes, after accounting for preexisting fuel taxes and carbon pricing.



# Mitigating CO<sub>2</sub> Emissions and Scenarios

But energy transition will require huge amount of solar panels, batteries, windturbines, electric cars, electrolyzers

And huge investment in manufacturing plants

(e.g. > 120 billions to make the production lines (equipments and building) to make 1000 GW of PV)







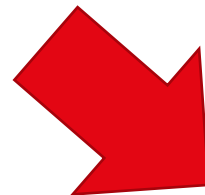
- China has done it during COVID

During the 3 years of COVID, chinese companies have invested massively in PV, batteries, electric cars and Wind.  
(>> 100 billions \$ invests)

- **In PV close to 1400 GW** of production capacity are online (500 GW PERC, 800 GW topcon, 100 GW SHJ and IBC.
- For batteries, soon capacity for 4800 GWh or 100 millions car per year equivalent



**Overcapacity (factor 2.5 to 3 for 2024)  
→ Ultra-harsh competition**



- PV at 10 cts
- Battery cell at 50\$/kWh
- Windturbine at 40 cts/W
- Inverters at 3cts/W
- Electrolysers systems at 30 cts/W



- China will « fight » against Oil and gas producer and try to export its technologies (good for mankind !), including electric cars. It is a new (and welcome for the climate) **geopolitical situation**
- But China ultra-dominance → risk to destroy remaining industry elsewhere  
→ Inflation reduction act (IRA) in USA, NZIA in Europe (too slow) ..., trade barrier, CO2 border tax
- Security challenges linked to most grid-connected power electronics controlled from china
- Resilience and EU production ?



Press Release

Press release: A Plea for Survival: ESMC Urges Swift Emergency Measures to support European PV manufacturing

January 17, 2024





# Toward Energy Transition

Some first steps  
Of course a lot in the power sector !

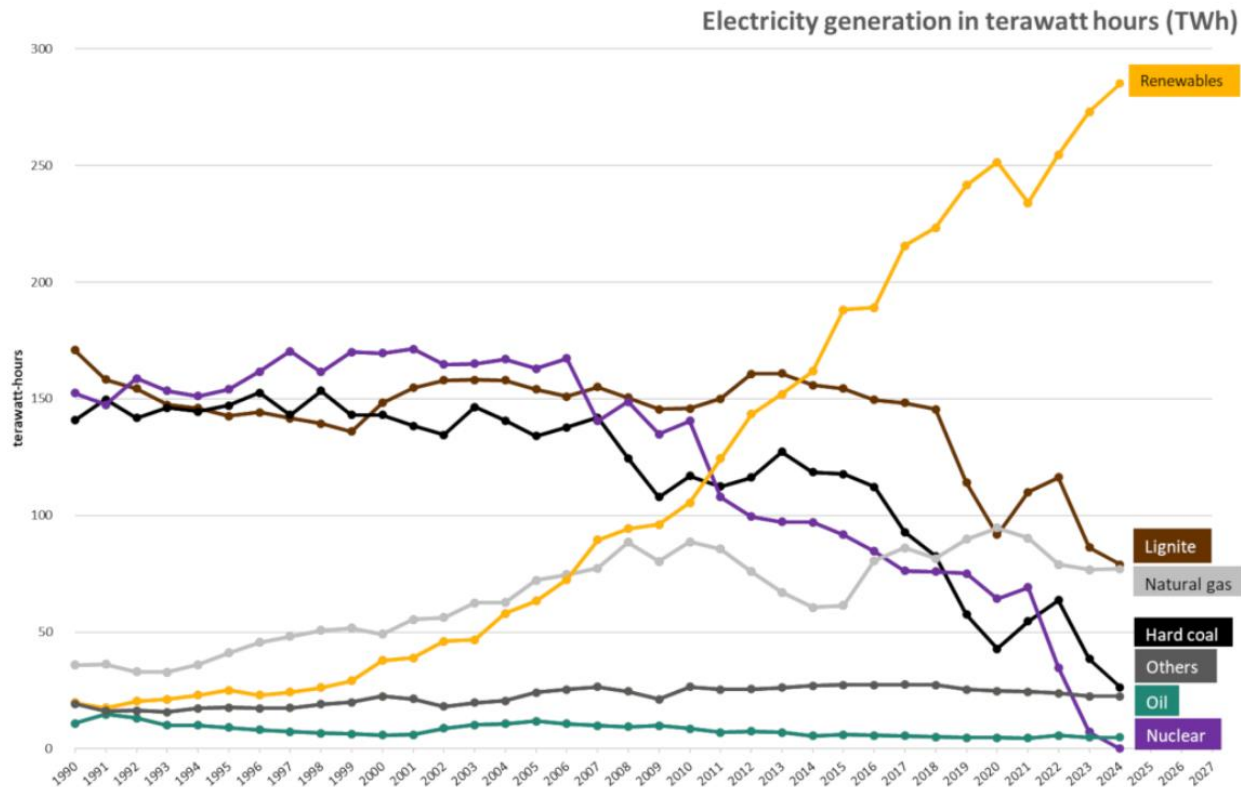


# Gross electricity production in Germany 1990 - 2024, by source.

Data: AGEB 2024.

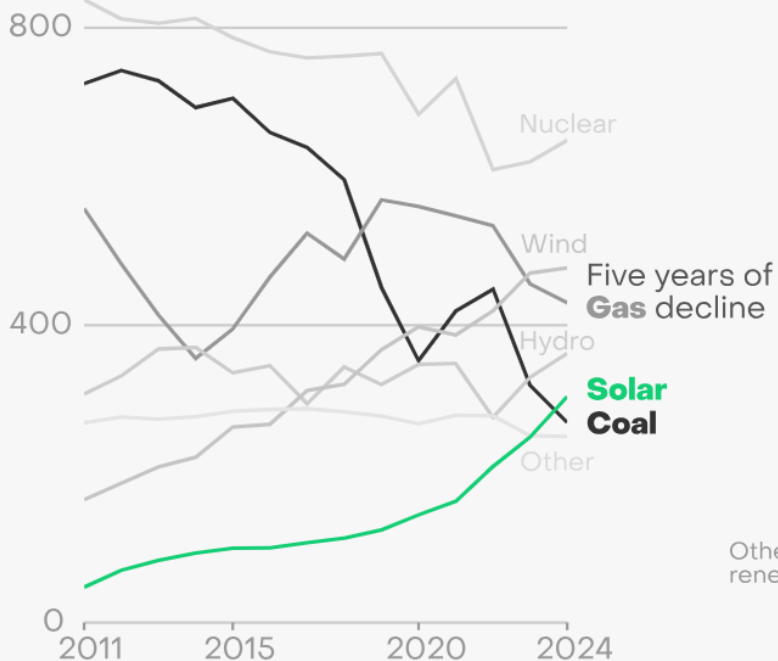


Germany increased share of new renewable s in Electricity

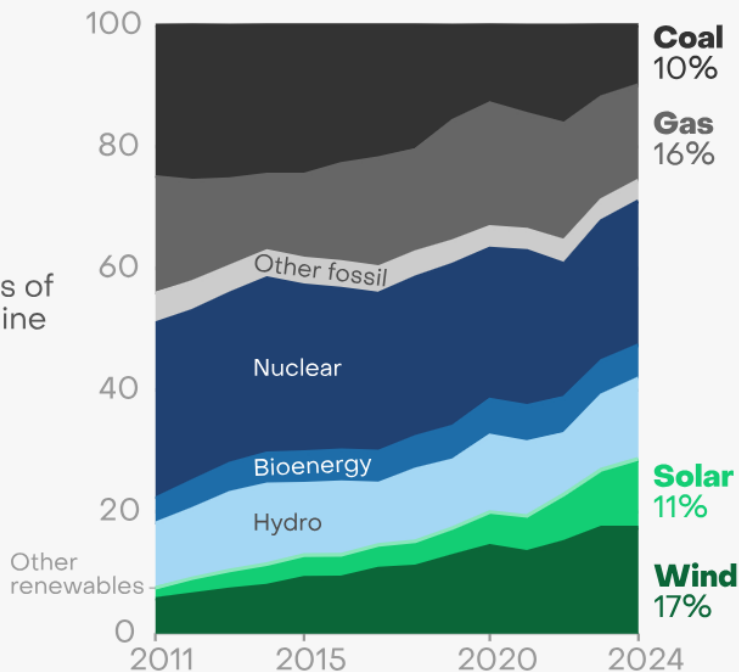


Solar overtakes coal generation in the EU for the first time in 2024

Electricity generation (TWh)



Share of generation (%)



**2024: 28% from wind (17%) and solar (11%) in Europe up from 23% in 2022, and 1.5% in 2000.**

**Wind surpasses gas for the first time in 2023**

**Renewables > fossiles for electricity**

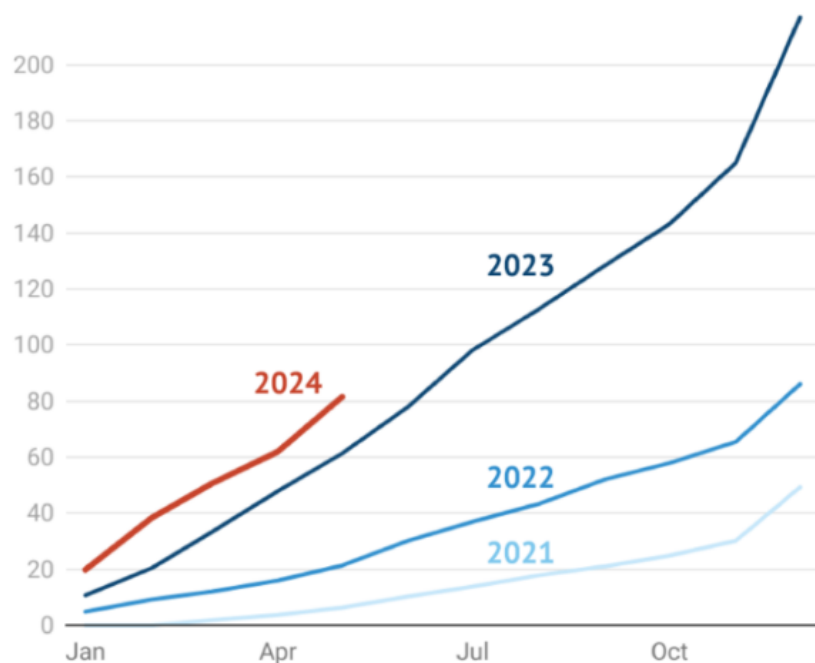
# China's wind and solar growth continues to break records in 2024

Cumulative new capacity per year, GW

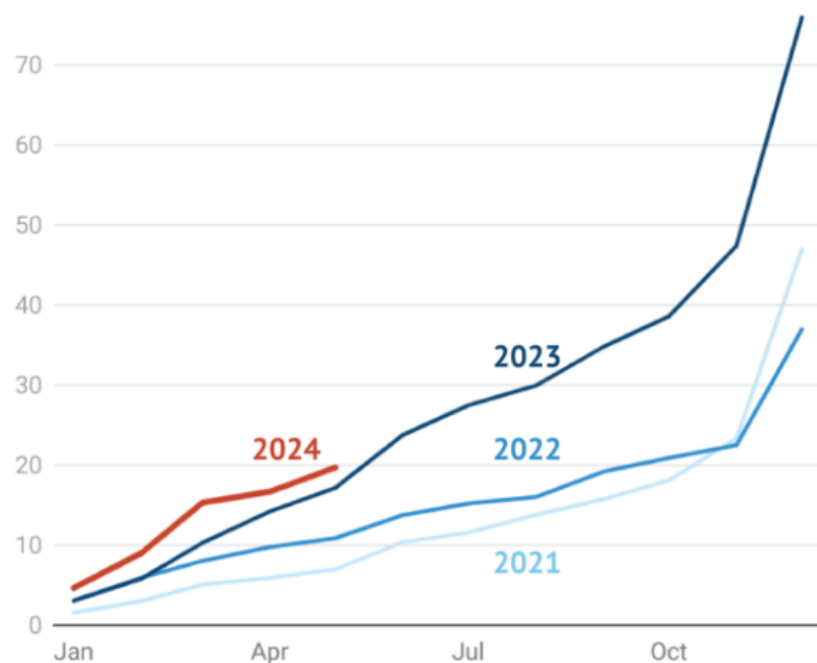


PV-lab  
IEM NEUCHÂTE

## Solar



## Wind

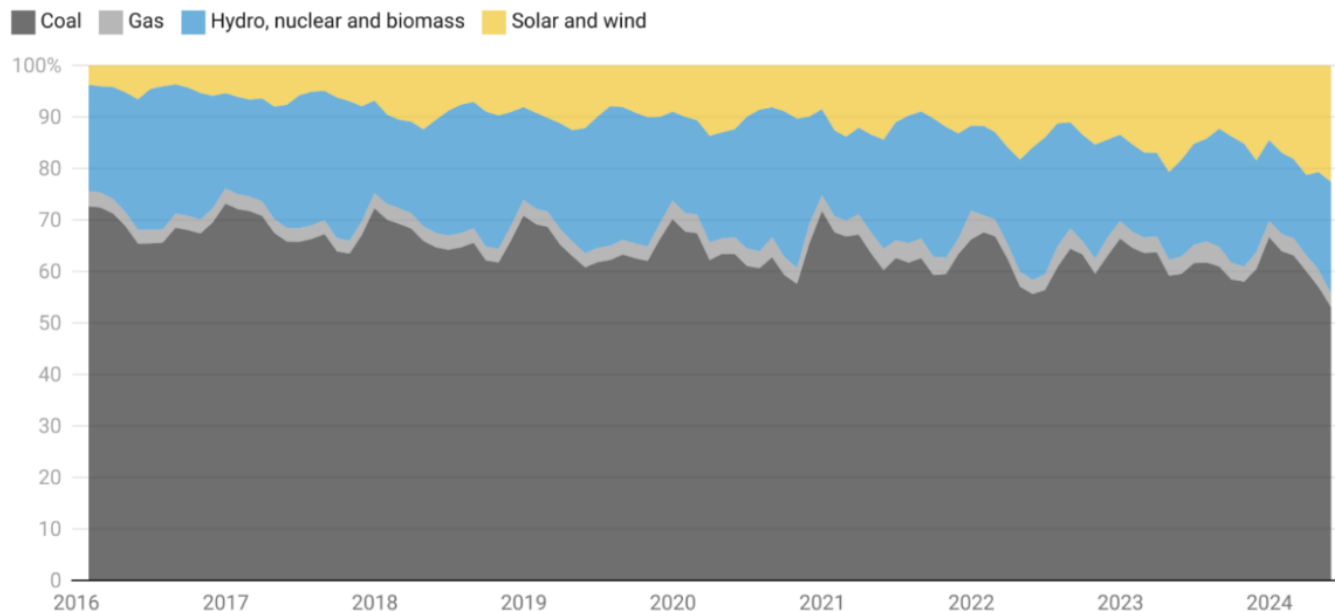


Source: National Energy Administration

# China increasing share of renewables but coal still growing

## Coal fell to a record-low 53% share of China's electricity in May 2024

Share of electricity generation, %



Source: China Electricity Council and National Bureau of Statistics



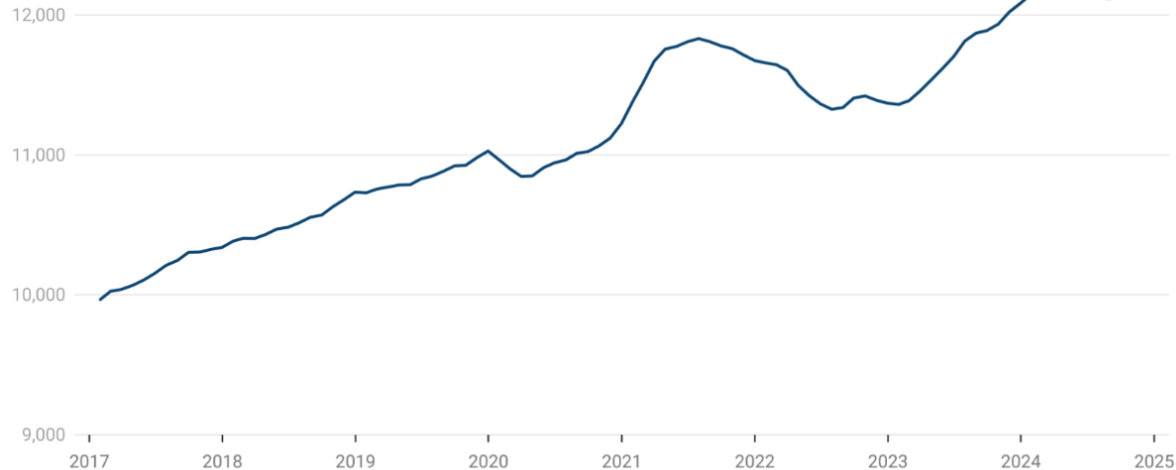
This guest post is by:

**Lauri Myllyvirta**, lead  
analyst at the Centre for

A record surge of clean energy kept China's carbon dioxide (CO<sub>2</sub>) emissions below the previous year's levels in the last 10 months of 2024.

### China's CO<sub>2</sub> emissions have plateaued since February 2024

Emissions from fossil fuels and cement, MtCO<sub>2</sub>, rolling 12-month totals

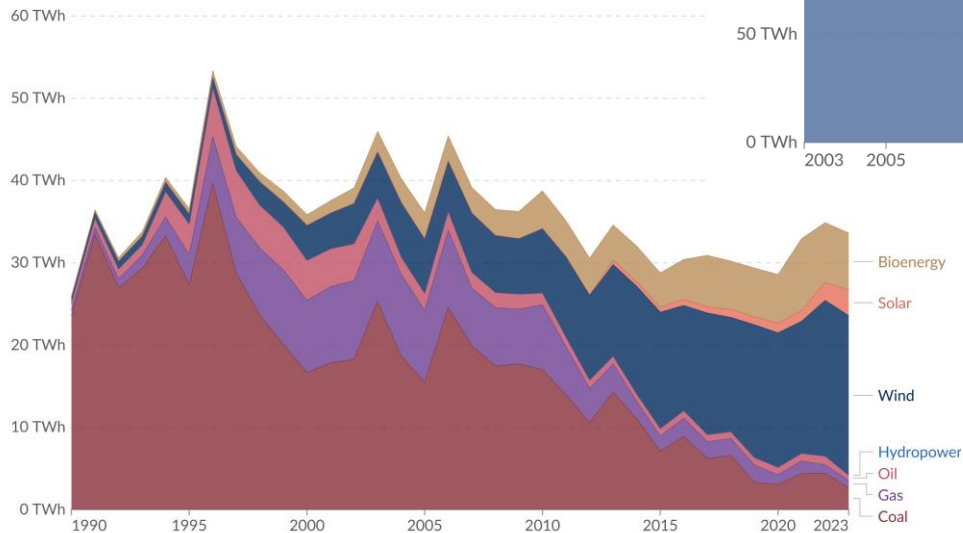


Source: National Bureau of Statistics, China Customs data, WIND Information and National Energy Administration



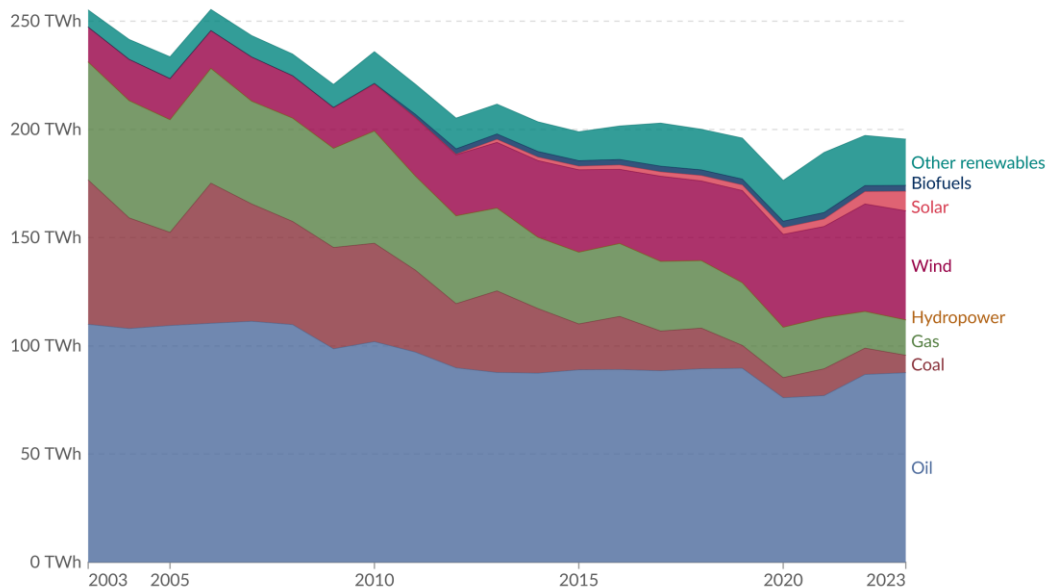
## Electricity production by source, Denmark

Measured in terawatt-hours<sup>1</sup>.



## Energy consumption by source, Denmark

Measured in terms of primary energy<sup>1</sup> using the substitution method<sup>2</sup>.



From 300 to 200 TWh  
Primary energy (substitution method)

# What was the 4th largest country installing in pv installation 2024

## ‘The Solar Blitz’: How crisis-ridden Pakistan is leading the world on the ‘Solar March’

Karl-Heinz Remmers examines Pakistan’s startling growth in solar energy use, which could serve as an inspiration not only for developing countries but also for Germany and the EU.

MARCH 4, 2025 **PV MAGAZINE**

[‘The Solar Blitz’: How crisis-ridden Pakistan is leading the world on the ‘Solar March’ – pv magazine International](#)

In 2024, Pakistan will have installed as much new photovoltaic capacity as rich Germany?  
**Over 16 GW?**

*“Anyone can get involved — the technology forgives many mistakes and is largely “plug and play”. The Pakistanis are also used to bridging their grid problems with diesel generators or batteries of all kinds, and now both solar modules and batteries are cheaper than ever and available in large quantities. Thanks to the good relations with China, there are no tariffs standing in the way of taking advantage of the low prices in Pakistan.”*

What it really takes to decarbonize? The example of Switzerland



Scenario for a partially decarbonised Switzerland:  
Typically 50 GW (by 2050) PV, working in conjunction with hydro + wind (~ 5-7TWh) + biomass (e.g. distance heat, biogas)

- Efficiency (save 12 TWh electricity)
- Electric cars
- Heat-pumps

→ 86-100% CO2 reduction

In book: worst case Keeps CO2 emissions for 9 TWh winter (not enough solar), e.g. gas power plant

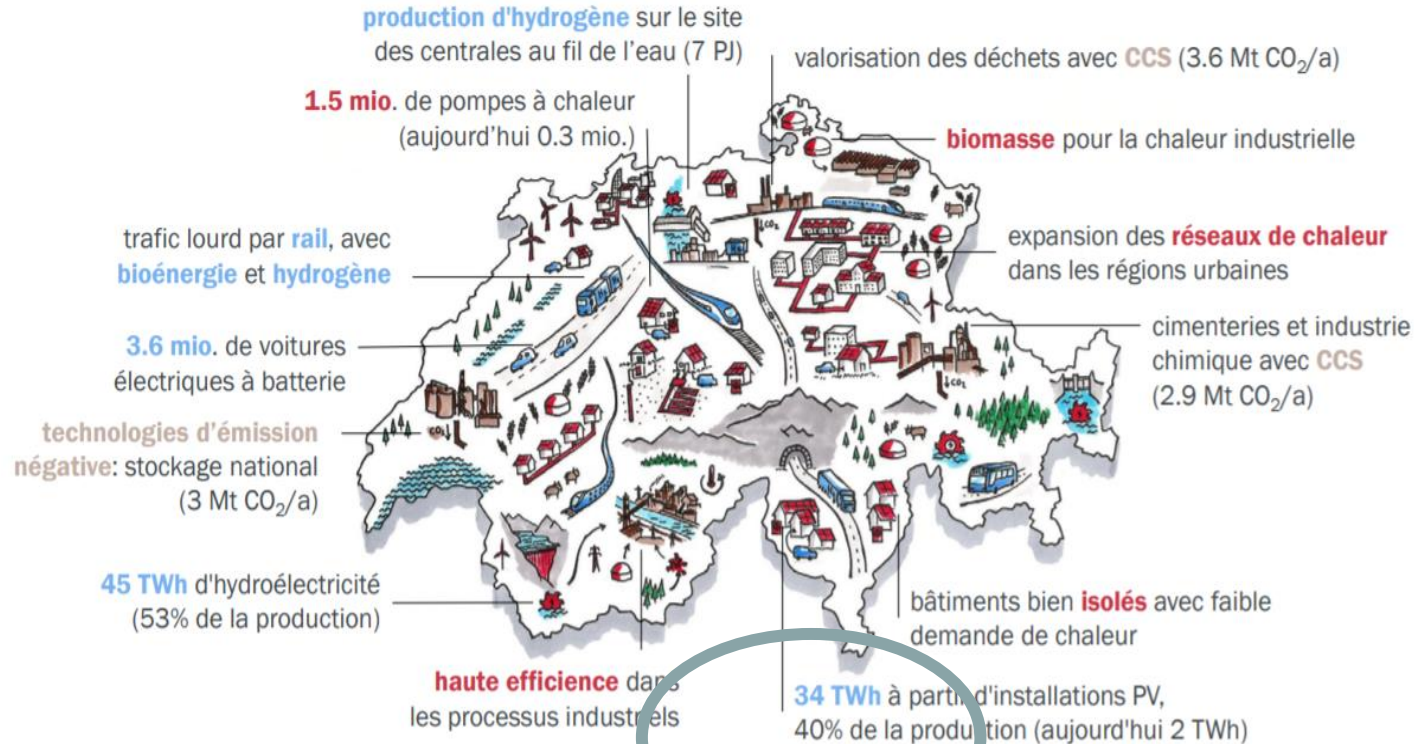
or use H2 (import or local), or produce/import wind electricity.

Upsides: more hydro, delay dam emptying, more solar in high altitude, more wind, keep biomass/biofuel.....

To be discussed in Final lecture



OBJECTIF D'UNE SUISSE NEUTRE POUR LE CLIMAT EN 2050



Study  
Of Swiss  
Federal office  
For Energy  
26.11.2020

37 GW PV  
(not much  
wind)  
For 9 millions  
people  
By 2050  
(n.b. 50 GW in  
Nordman  
scenario)

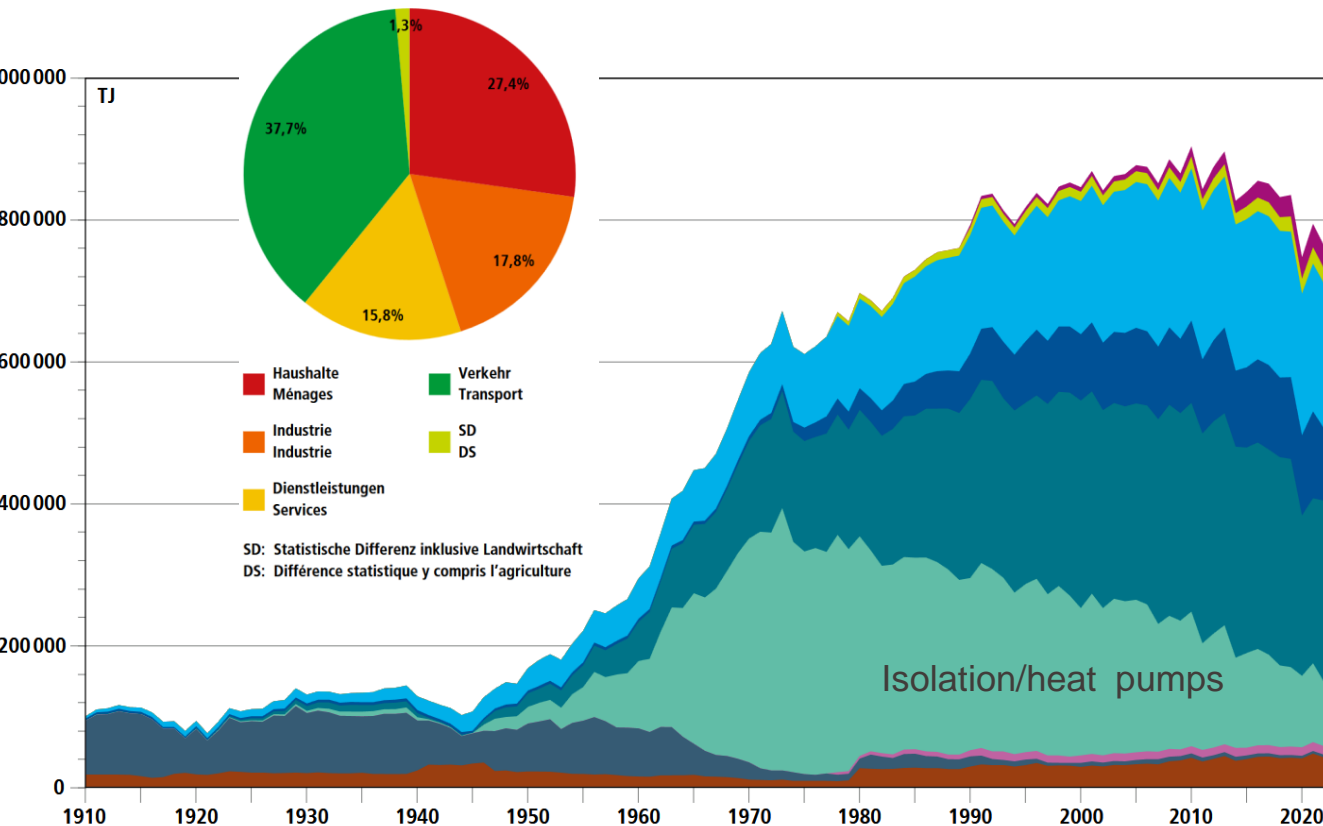
Now 45 TWh  
new renewable  
in gov plan for  
2045. To be  
voted on in  
June

# Swiss final energy consumption up to 2023



212 TWh

Anteil 2023 der vier Sektoren in %  
Parts en 2023 des quatre secteurs en %



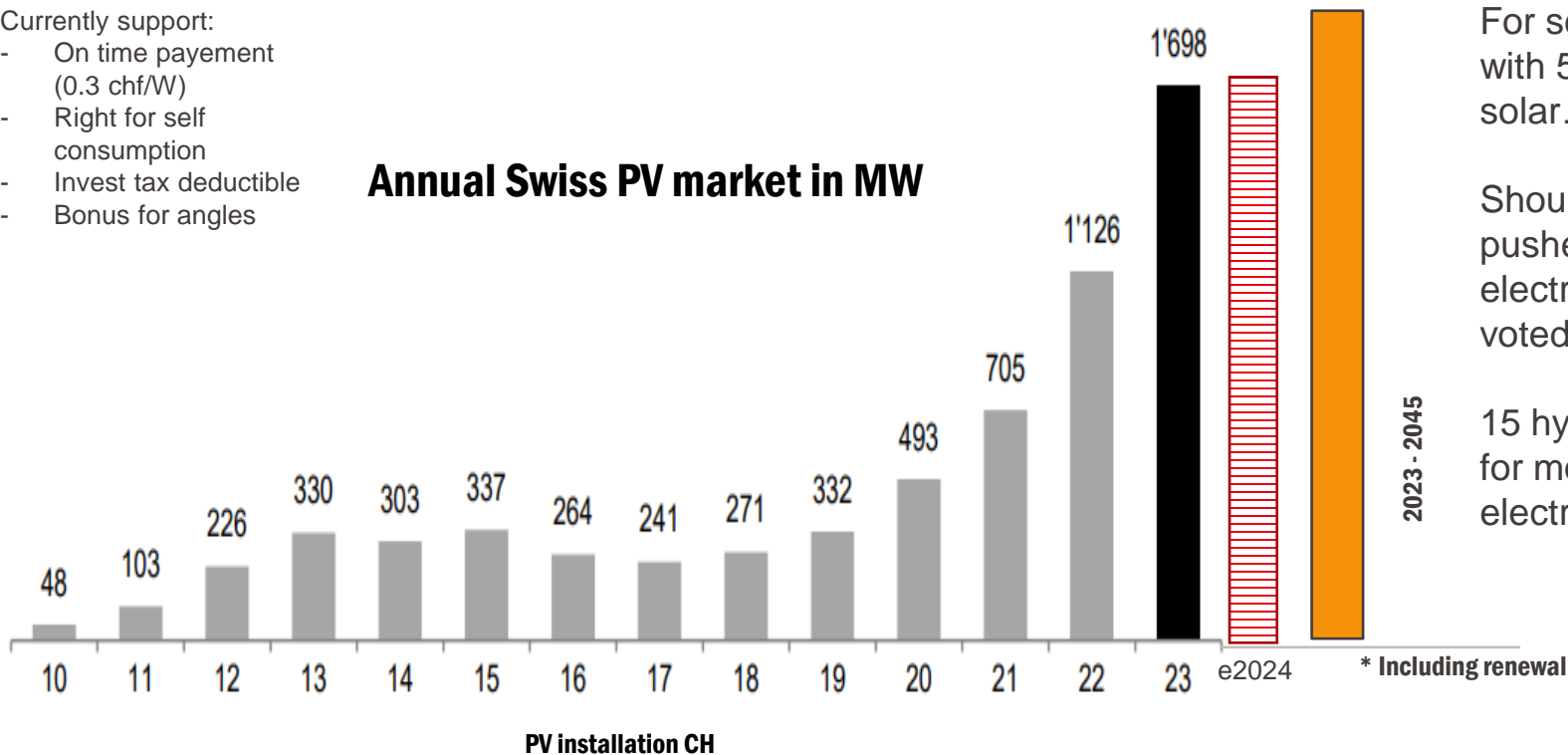
- 27% Übrige erneuerbare Energien  
Autres énergies renouvelables
- 15% Fernwärme  
Chaleur à distance
- 30% Elektrizität  
Electricité
- 14% Gas  
Gaz
- Treibstoffe  
Carburants
- Erdölbrennstoffe  
Combustibles pétroliers
- Industrieabfälle  
Déchets industriels
- Kohle  
Charbon
- Holz  
Bois

End 2024: 7.7 GW installed  
~11 % of annual CH electricity  
consumption of 2024

Currently support:

- On time payment (0.3 chf/W)
- Right for self consumption
- Invest tax deductible
- Bonus for angles

## Annual Swiss PV market in MW



Min > 1.7 GW  
year

For scenarios  
with 50 GW  
solar....

Should be  
pushed with new  
electricity law  
voted in 2024 !

15 hydro projects  
for more winter  
electricity

Orders of magnitudes starts to be ok !



# PERSPECTIVE WITH SOLAR AND WIND

- Desalination (down to 0.5\$/m<sup>3</sup> desalinated)
- H<sub>2</sub> → direct NH<sub>3</sub> for fertiliser and later energy vector or direct industrial use of H<sub>2</sub>
- Later direct carbon capture

Photovoltaics at multi-terawatt scale: Waiting is not an option

| Science 2023

Scenarios with 75'000 GW  
PV by 2050



See projects in Morocco, with

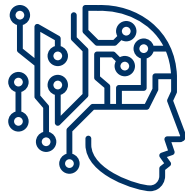
- OCP target of green fertiliser with ammonia
- 10'000 km<sup>2</sup> reserved for green industry, in highly sunny and windy climate
- Close to 100 companies expressed interests for e.g. steel decarbonation



1. In the current EU electricity mix, renewable energies generate more than fossil fuels.
  - a) True.
  - b) False.
  - c) I'm not sure...
  
2. From IRENA's 2022 estimations, by 2050 these will be the main contributors to the electricity generation (in order from most to least).
  - a) Solar, wind and Nuclear.
  - b) Hydropower, wind and solar.
  - c) Wind, solar and hydropower.
  
3. By a fully decarbonized 2050, which one of the renewable technologies will grow most?
  - a) Wind and solar
  - b) Geothermal
  - c) Nuclear

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# TO SUMARIZE: MAJOR TECHNOLOGICAL ROUTES FOR THE ENERGY TRANSITION



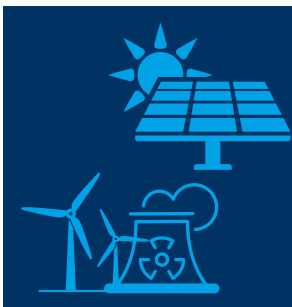
**Flexibility and intelligence**



Public transport  
or **electric cars**  
+  
**batteries**



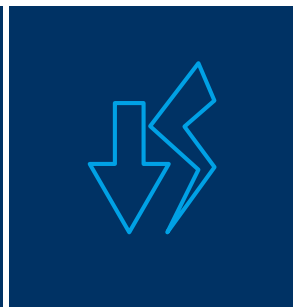
**Heat pumps**  
(air, geothermal  
water, CO<sub>2</sub>)



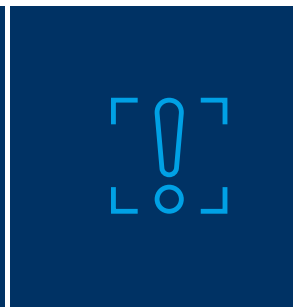
**Solar, Hydro,  
Wind, Biomass**  
(Nuclear)



**Insulation,  
efficiency**



**Tracking  
losses**



**+ many small  
(but important)  
+ H<sub>2</sub> ....  
+ ships and plane**

# EPFL Fighting global warming: «what should happen» globally

## ■ Develop massively wind and solar

Other sources: biomass, hydro, geothermal

Maintain (or develop) nuclear base to facilitate transition

Keep and optimise fossil fuel assets for flexibility (but low capacity factor)

Capitalise on electrochemical storage (batteries) and synergies with mobility

Necessary amount of power-to-gas... (industry, heat, peak power). Keep small !

Keep biofuels mostly for peaks, air and maritime transport where difficult to replace

## Agriculture

Sequestration through biomass and soils

Less cattle emitting CO<sub>2</sub>

## Strategy

Local production (including of energy products)

Resources (metals, lithium, ...)

Manpower: educate, prioritize and pay better

Intelligence: control and flexibility of energy systems

## ■ Energy efficiency

Switch to electrical (transport, heat pumps)

Isolate building

Track losses (ventilation pumps),...

## Sufficiency

Rethink consumption (smaller room, no flight, less or no red meat,...). Accept less in critical period (e.g. lower heating T of buildings)

Reduce cement and capture CO<sub>2</sub> Long term: Sequester carbon (from the air)

# Mitigating CO<sub>2</sub> Emissions and Scenarios: summary

- Energy transition could be made at World, European and Swiss level
- Primarily by switching to renewable energies in all forms, cheaper in terms of LCOE, and keeping part of fossil fuel assets as reserve
- Costs saving on LCOE to adapt the system (grid, storage)
- Global investments acceptable, nothing if one considers external costs of fossil (impact of global warm, health issues and biodiversity...)
- Improve effort at efficiency, consumption reduction
- Carbon storage at best in reforestation and ground management, can contribute to mitigate
- A greener agriculture, with less meat will also help
- Going fast is possible (see the German case) without damaging the economics... borrow money to invest for tomorrow

**But energy unless you stop the economy, transition will require huge amount of solar panels, batteries, windturbines, electric cars, electrolyzers**

