Energy Transition : Modeling and Scenario Analysis

Introduction

Sylvain Quoilin, 2025

Organization

Lecturers

- **Sylvain Quoilin**
- Chercheur Qualifé FNRS
- Head of the ISES Research Team within the Thermodynamics Laboratory (B49)
- Experience:
  - TU München, MIT
  - European Commission
  - Formerly professor at KU Leuven
- squoilin@uliege.be

- **Julien Jacquemin**
- Researcher within the ISES group
- Responsible for the exercice sessions
- Julien.Jacquemin@uliege.be

Course objectives

Be able to answer the following questions:

- What are the main challenges, debates and controversies and in the energy transition?
- How to apply optimization techniques to model the energy transition?
- How to implement optimization, in which language, and with which software?
- Which solver to use for which type of problem?
- How are energy scenarios and energy planning built?
- Which model formulation is the most adapted to different kinds of problems?
- How to simulate a complex energy system accounting for: optimal dispatch, interconnections, storage, capacity expansion, variable renewable energy, sector coupling, user behavior, uncertainty, environmental impacts.
- How to interpret the outcomes of these problems and link them to policy interventions, energy markets & systems?

Content

Three main parts:

- Lectures
    - Every week, ~2h
    - Theoretical background
    - General considerations about energy & sustainability
    - Participation welcome!
- Exercise classes
    - Every week, ~2h
    - Simplified examples of real-life problems
    - Start from a simple model, and complexify it by adding new features
    - All exercises are done in jupyterhub (http://thermopython.uliege.be/)
    - Bring a computer!
- Individual home assignment:
    - Students participating in the Energy Challenge:
        - Formulate the multi-energy problem of the campus optimization
        - Include the concepts discussed in the course
    - Other students:
        - Download and run an existing energy system model with its inputs data
        - Short report

Indicative schedule

- 4/2 Introduction
- 11/2 Unit commitment & optimal dispatch
- 18/2 Storage
- 25/2 Grids
- 11/3 Capacity expansion
- 18/3 Demands
- 25/3 Sector coupling
- 1/4 Uncertainty
- 8/4 IAMs
- 15/4 Climate models and scenarios (Xavier Fettweis)
- 6/5 Evolution of the Belgian climate (Xavier Fettweis)
- 13/5 Group work

Material

- Slides used during the lectures
  - Final version will be available after each lecture, preliminary version the day before
  - Sharing platform: http://thermopython.uliege.be/
- Coding examples and exercises available on the Jupyterhub platform
  - http://thermopython.uliege.be/
- Background reading material & references (not to be studied, for deeper understanding of topic at hand)

Evaluation

The evaluation is based on:

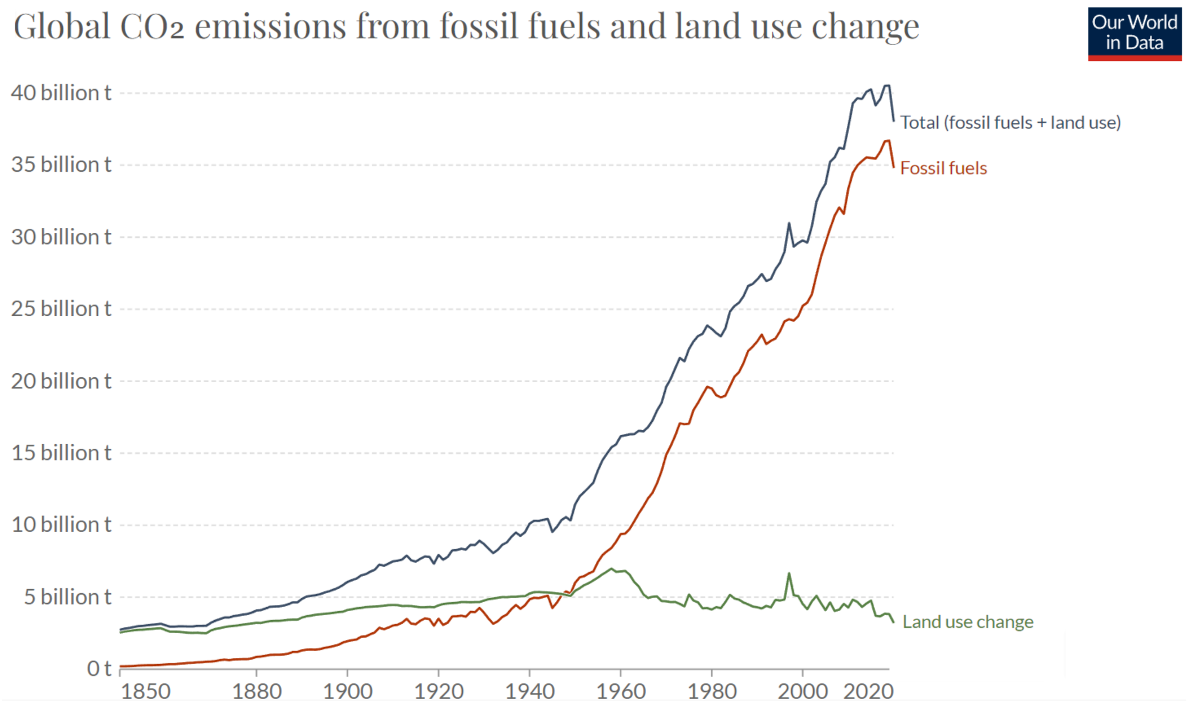
- Written exam AND oral exam
  - Ability to solve an exercise on the computer, similar to those done during the classes
  - Open-ended (oral) questions related to the optimization methods and the interpretation of the results
  - Open-ended questions related to the energy transition concepts mentioned during the classes
  - Counts for 60% of the final grade
- Personal project
  - Written report
  - Source code available on GitHub
  - Day-to-day assessment of the student involvement during the classes and for the project
  - Counts for 40% of the final grade

Round table

- Your name?
- What topic would you like for your future master thesis? Is this related to the content of this course?
- Any question?

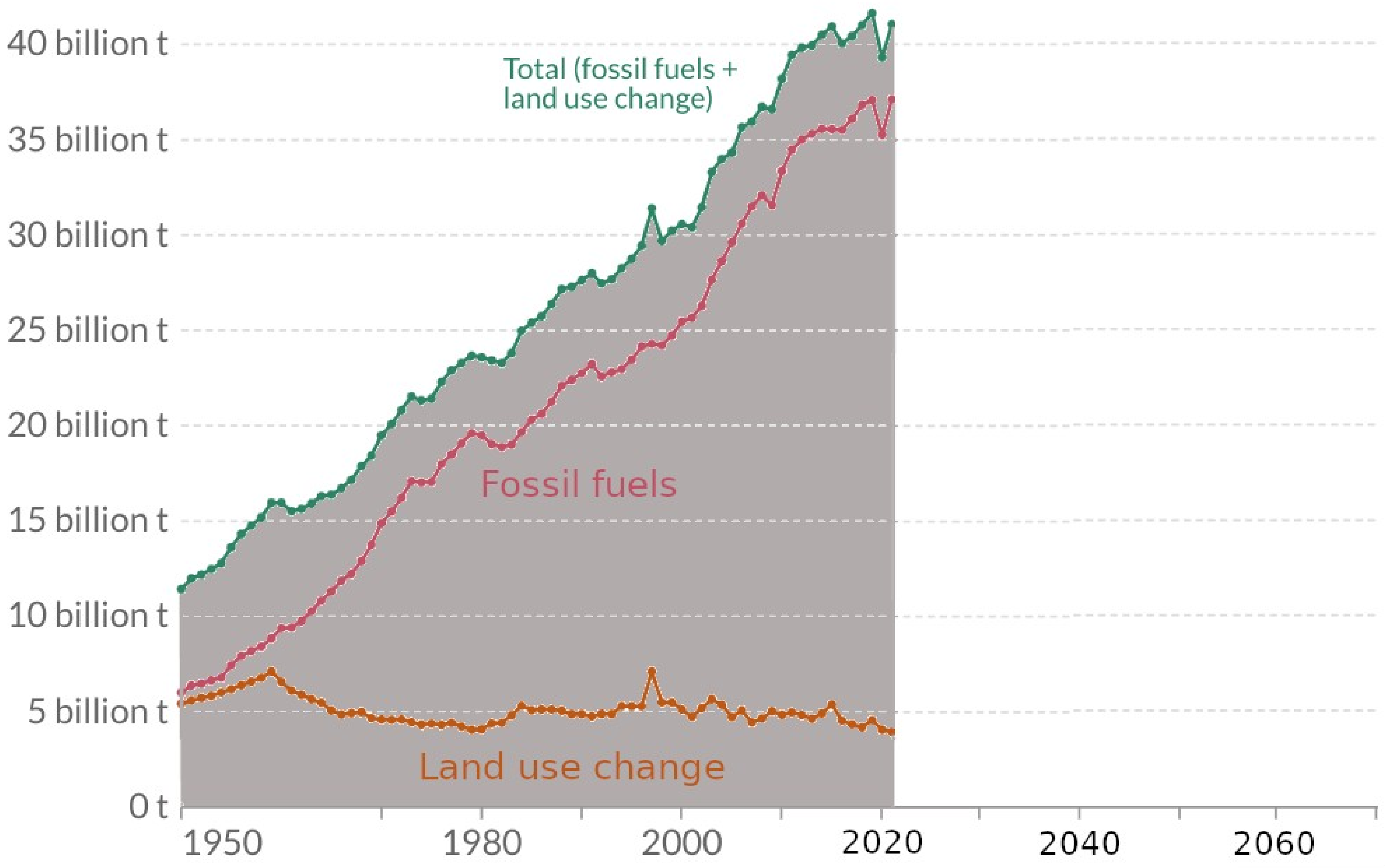
The importance of the Energy Transition

Carbon budget for the world

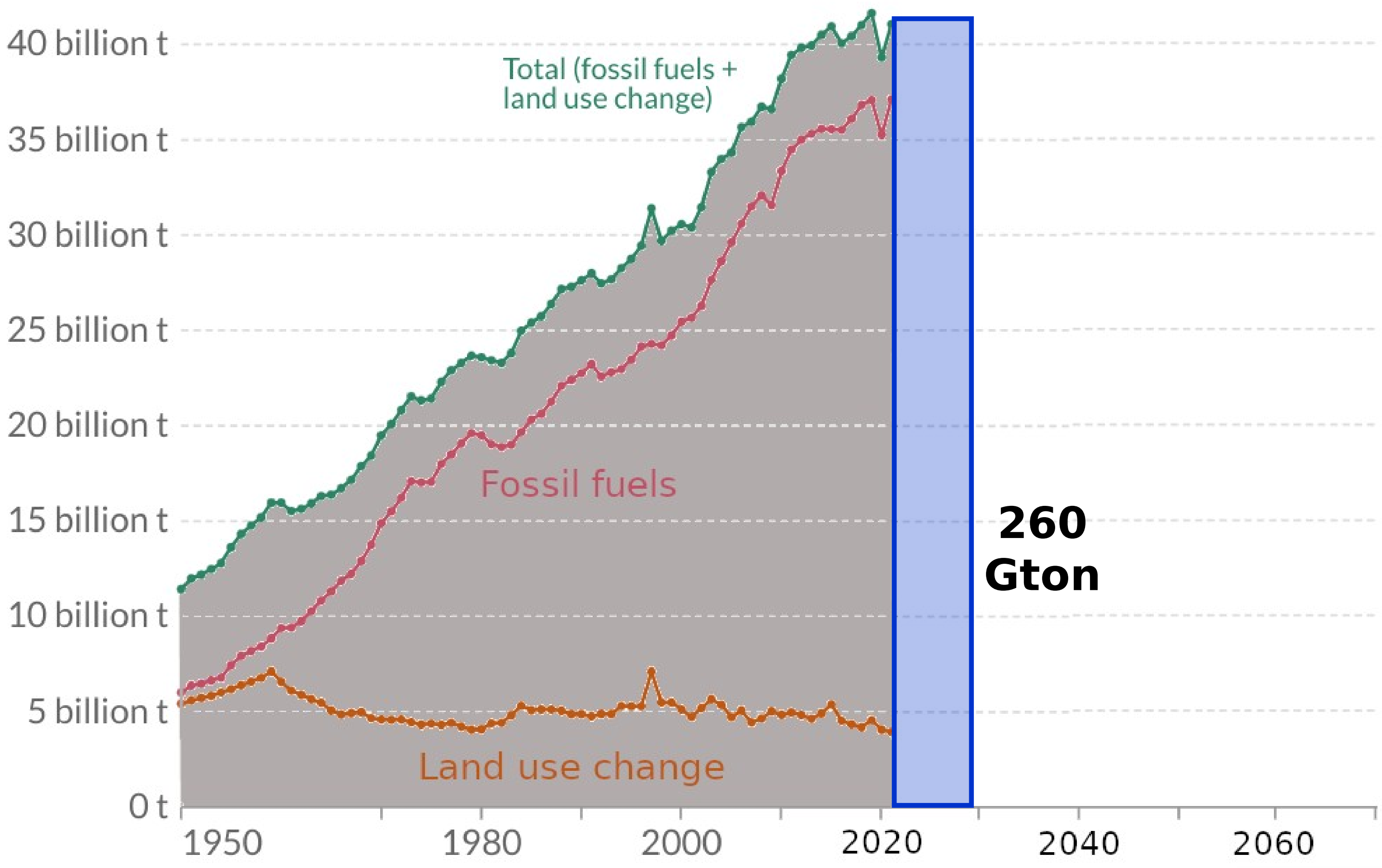


Likelihood of limiting global warming to temperature limit	Temperature limit of interest compared to preindustrial levels	Estimated remaining carbon bnudget from the beginning of 2020 ($GtCO_2$)	New esttimations in 2023 ($GtCO_2$)
50% 67%	1.5°C 2°C	510 (IPCC WGIII, 2022) 1000 (IPCC WGIII, 2022)	260 950

Carbon emissions

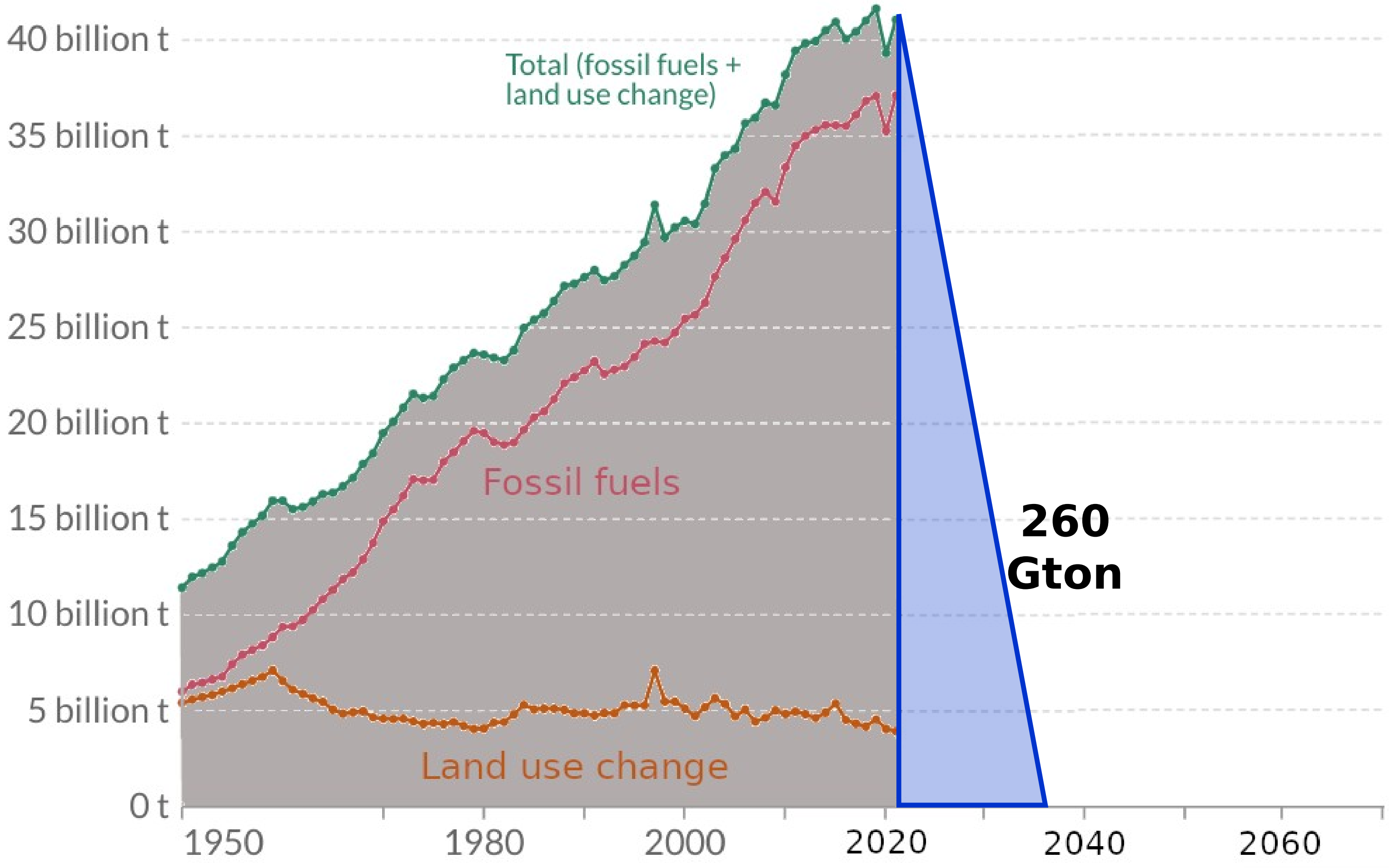


Carbon Budget



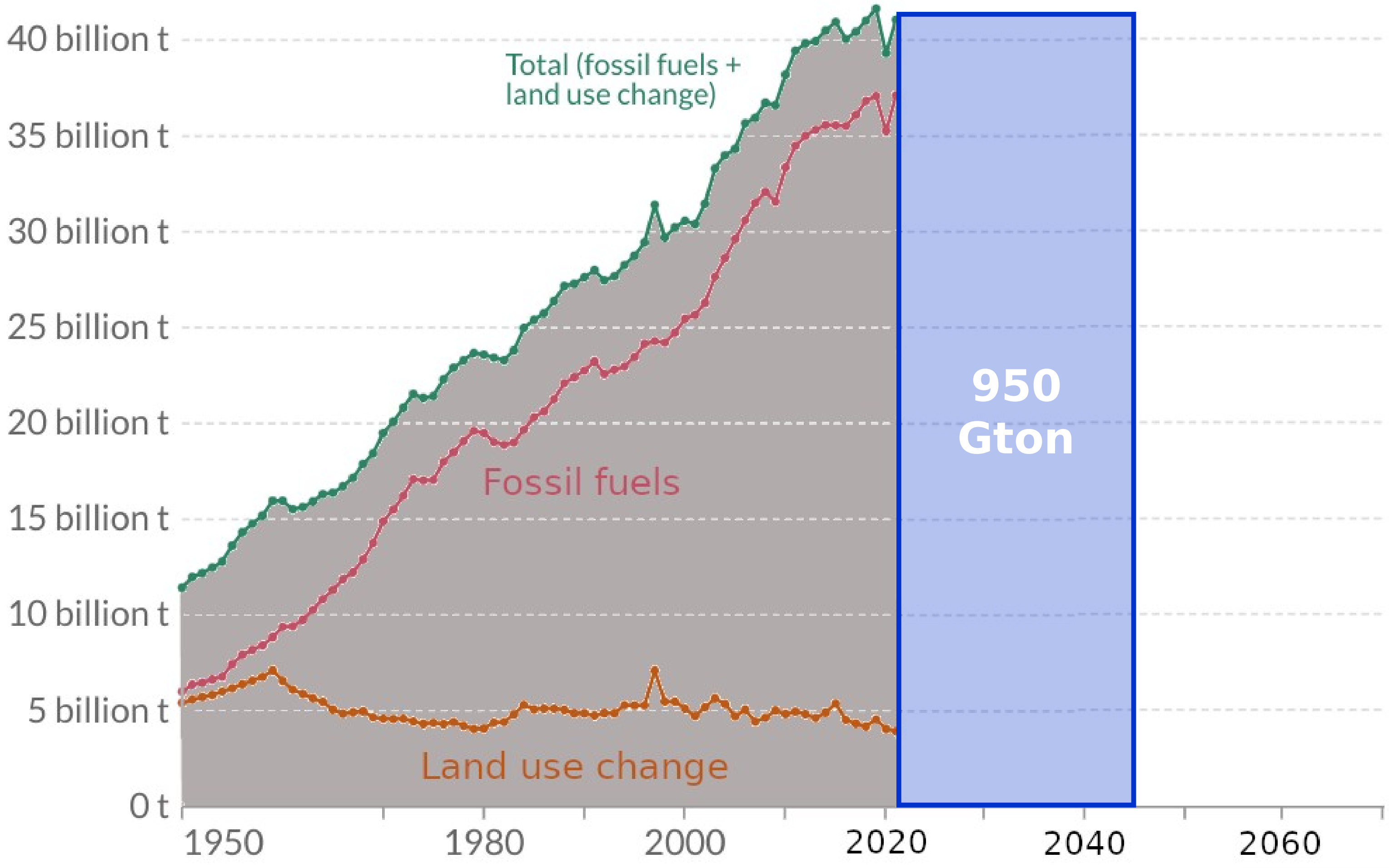
1.5°C
(with no or limited overshoot)

Carbon Budget



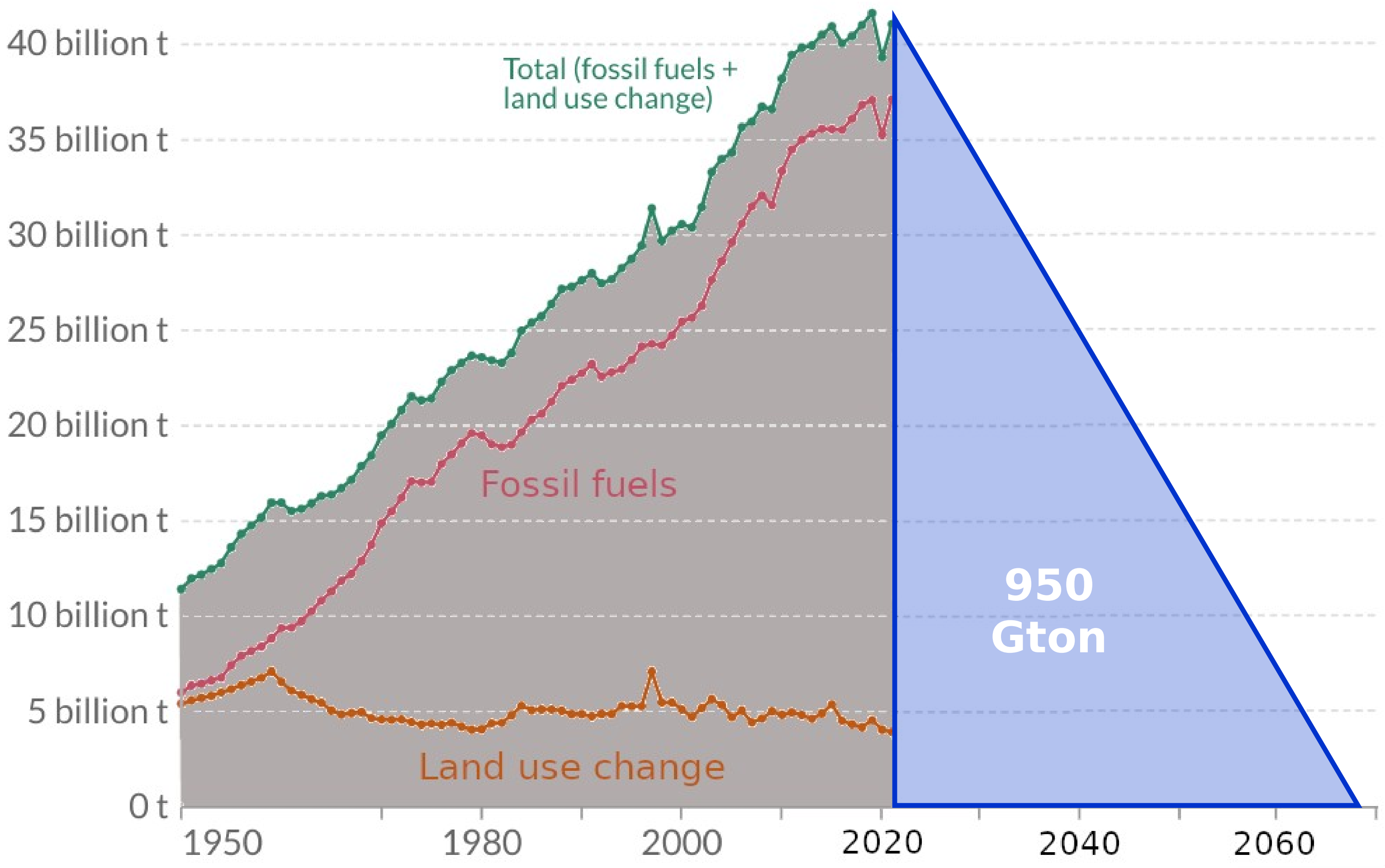
1.5°C (with no or limited overshoot)

Carbon Budget



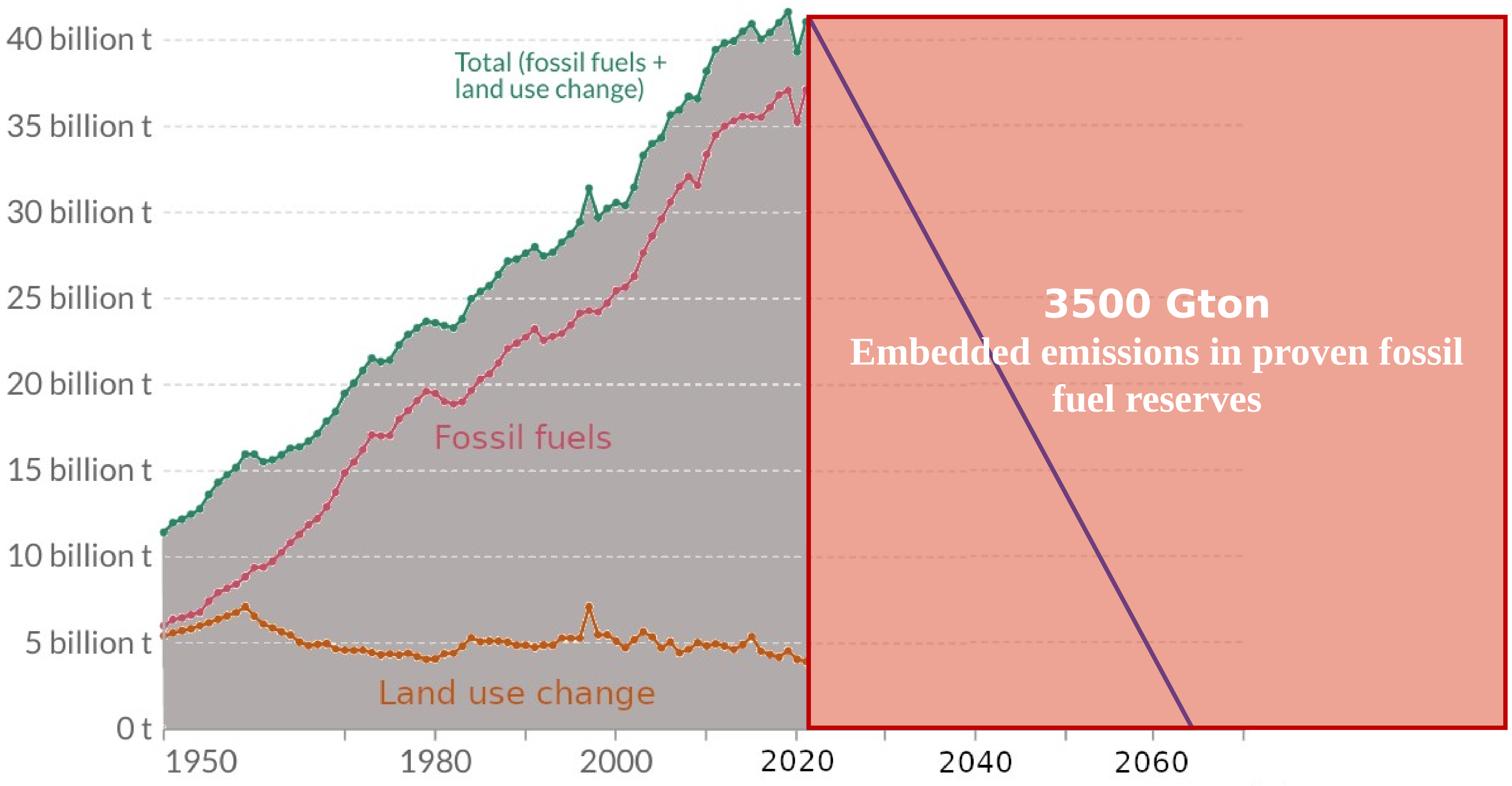
2°C (pathway likely limiting warning to)

Carbon Budget



2°C (pathway likely limiting warning to)

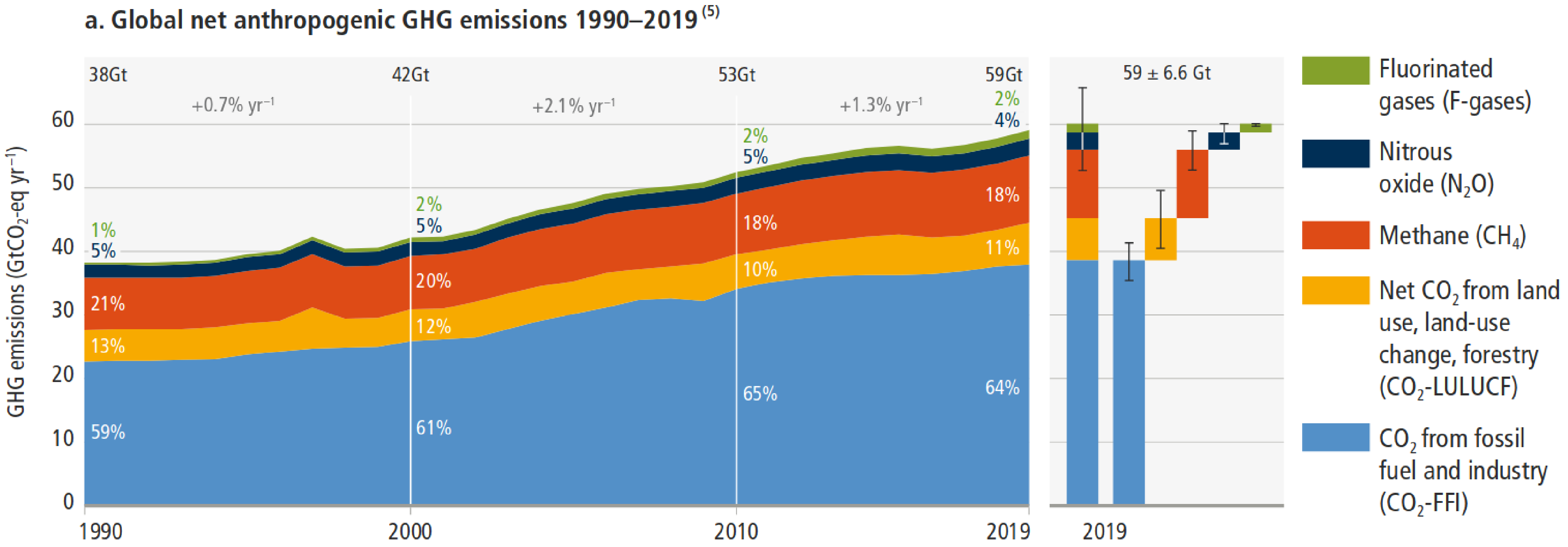
Unburnable carbon



Stranded assets to be retired earlier than expected lifetime (IPCC AR6 WGIII)

Data source: The Global Registry of Fossil Fuels (reported by The Guardian)

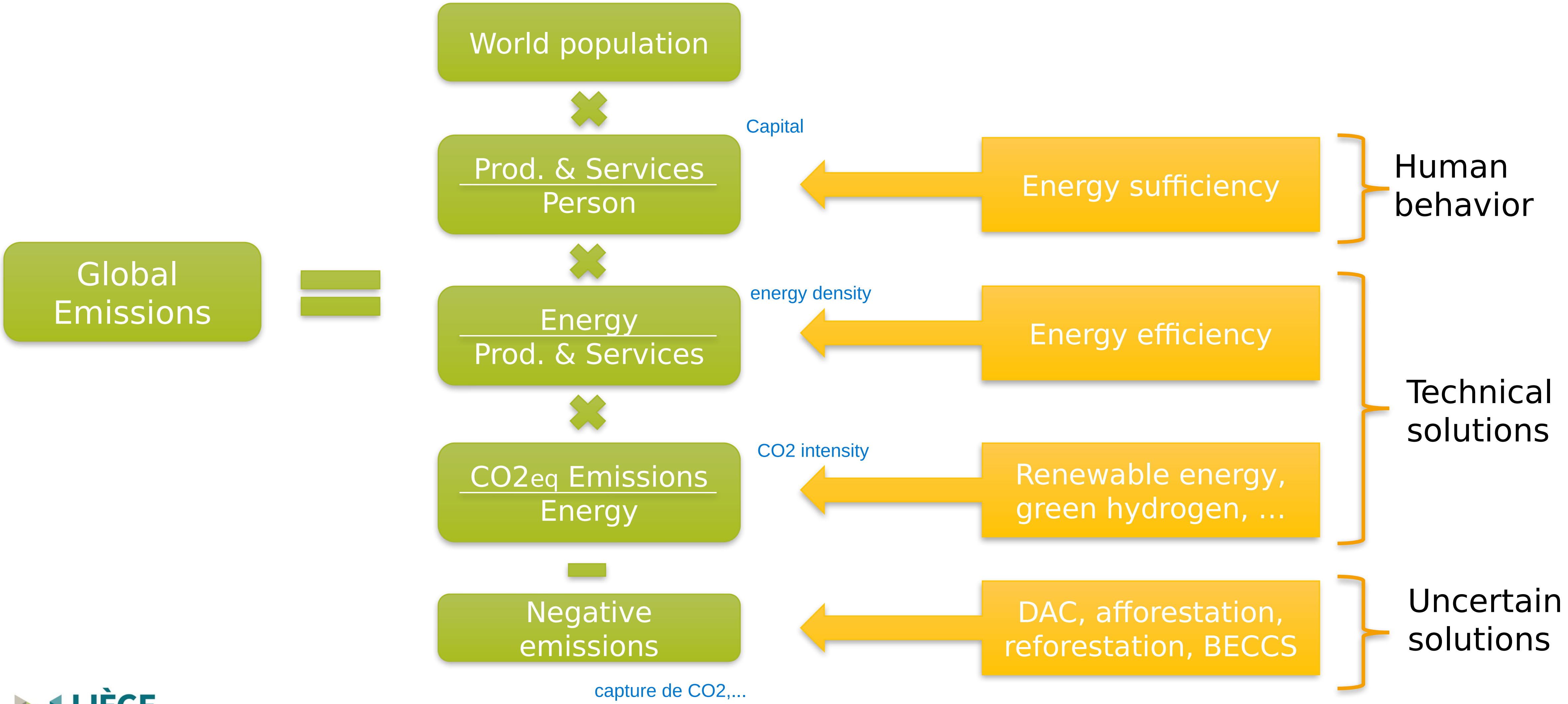
CO2 is not alone!



Source: IPCC AR6 WG3, 2022

Kaya's identity

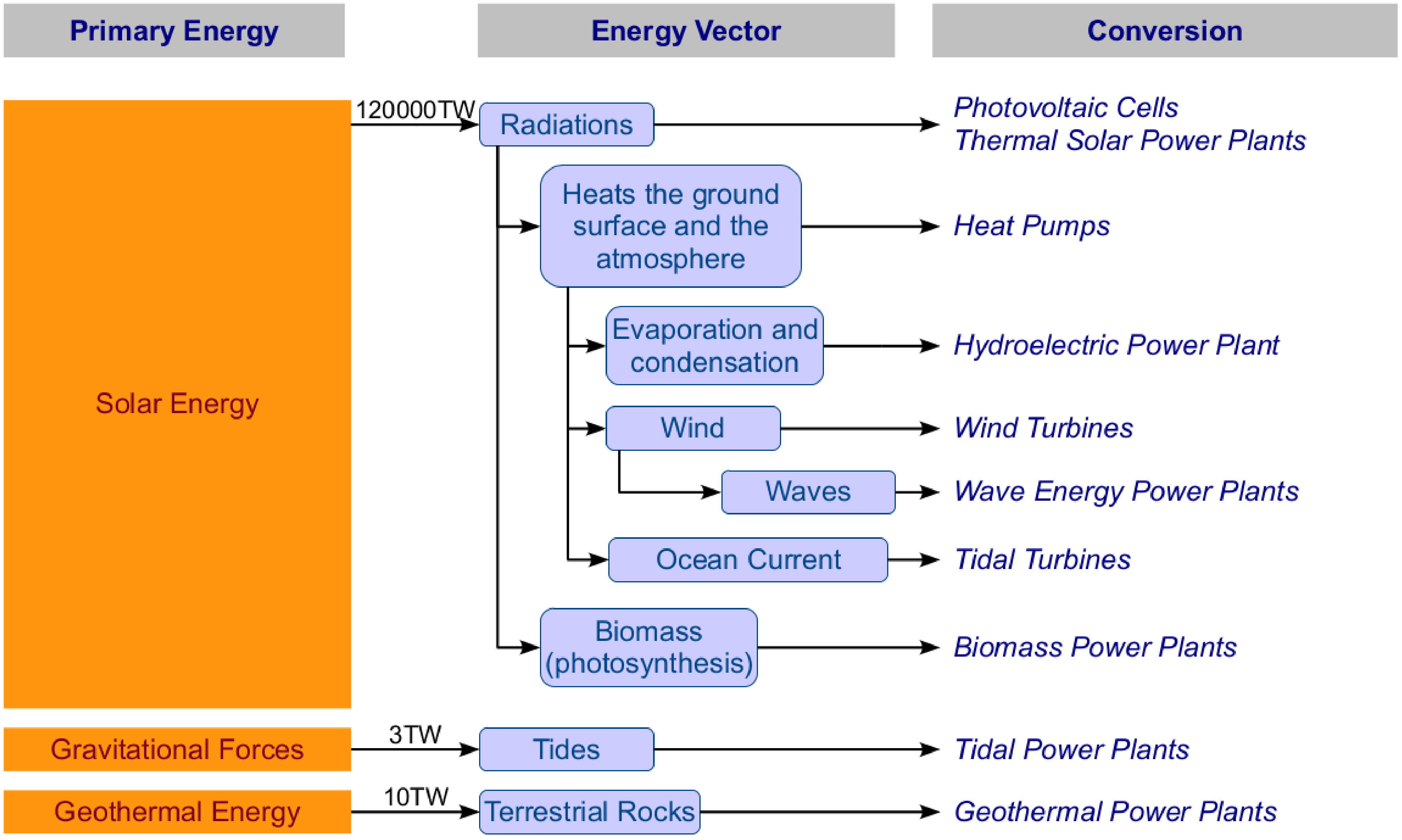
Energy sufficiency, efficiency and clean techs are complementary!



Adapted from B. Best, Suffizienz in deutschen Energiescenarien, 2021

Renewable energy

Where does renewable energy come from?



not renewable energy because cycle too much longer

Question

A flat surface perpendicular to the sunlight and located at the limit of the terrestrial atmosphere receives, on average:

$$C^* = 1366 \text{ W/m}^2 \pm 3\%$$

According to the IEA, the yearly world primary energy supply was 14 282 Mtoe (=166099 TWh) in 2018. Calculate how long it takes for the earth to receive this amount of energy from the sun.

NB: the radius of the earth is 6378 km

166099 * 10**12 / (1366* (pi* (6378* 10**3)**2)) = 1 hour

Offshore/Onshore Wind

Solar PV

Hydro

Biomass & Waste

Concentrating solar

Solar thermal

Ocean

Geothermal

Biogas

Biofuels

Offshore/Onshore Wind

2.0%

15.6%

Solar PV

9.1%

Hydro

11.9%

Biomass & Waste

3.4%

Concentrating solar

0.15%

Solar thermal

0%

Ocean

0.02%

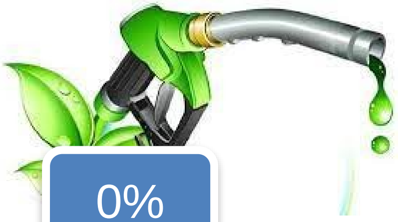
Geothermal

0.2%

Biogas

2.2%

Biofuels



0%

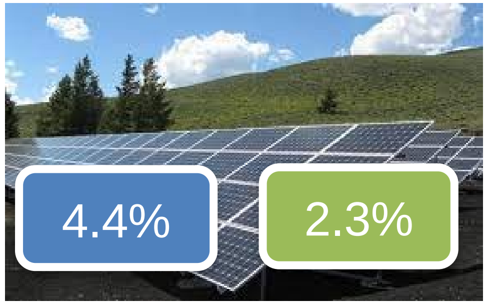
Share in electricity generation

Data source: EMBER European Electricity Review 2024

Offshore/Onshore Wind

2.0% | 0.4% | 15.6% | 4.9%

Solar PV



4.4% | 2.3%

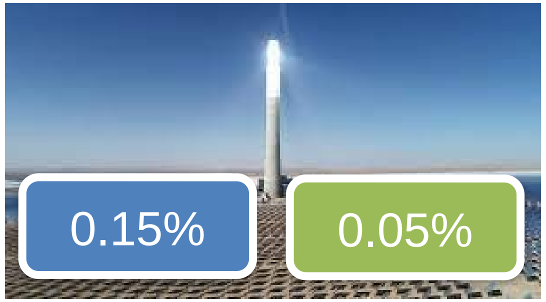
Hydro

11.9% | 4.0%

Biomass & Waste

3.4% | 10.9%

Concentrating solar

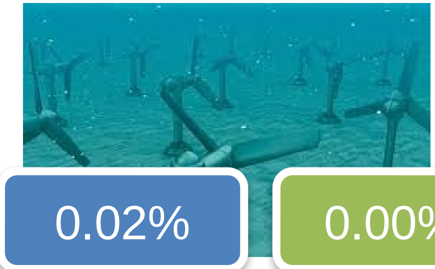


0.15% | 0.05%

Solar thermal

0% | 0.02%

Ocean

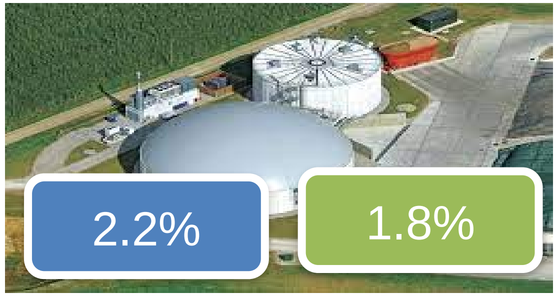


0.02% | 0.00%

Geothermal

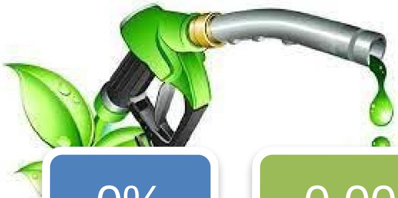
0.2% | 0.1%

Biogas



2.2% | 1.8%

Biofuels



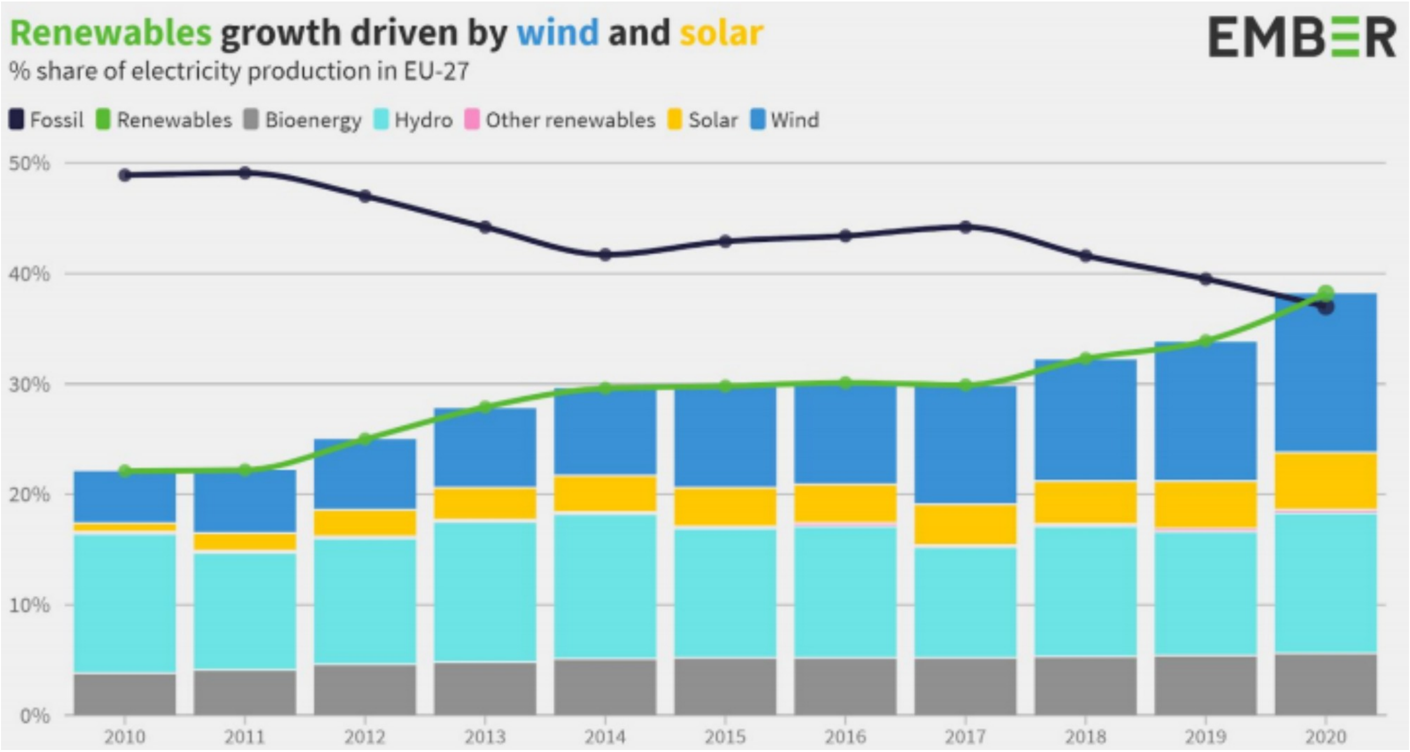
0% | 0.002%

for example enegry is too heat or cold

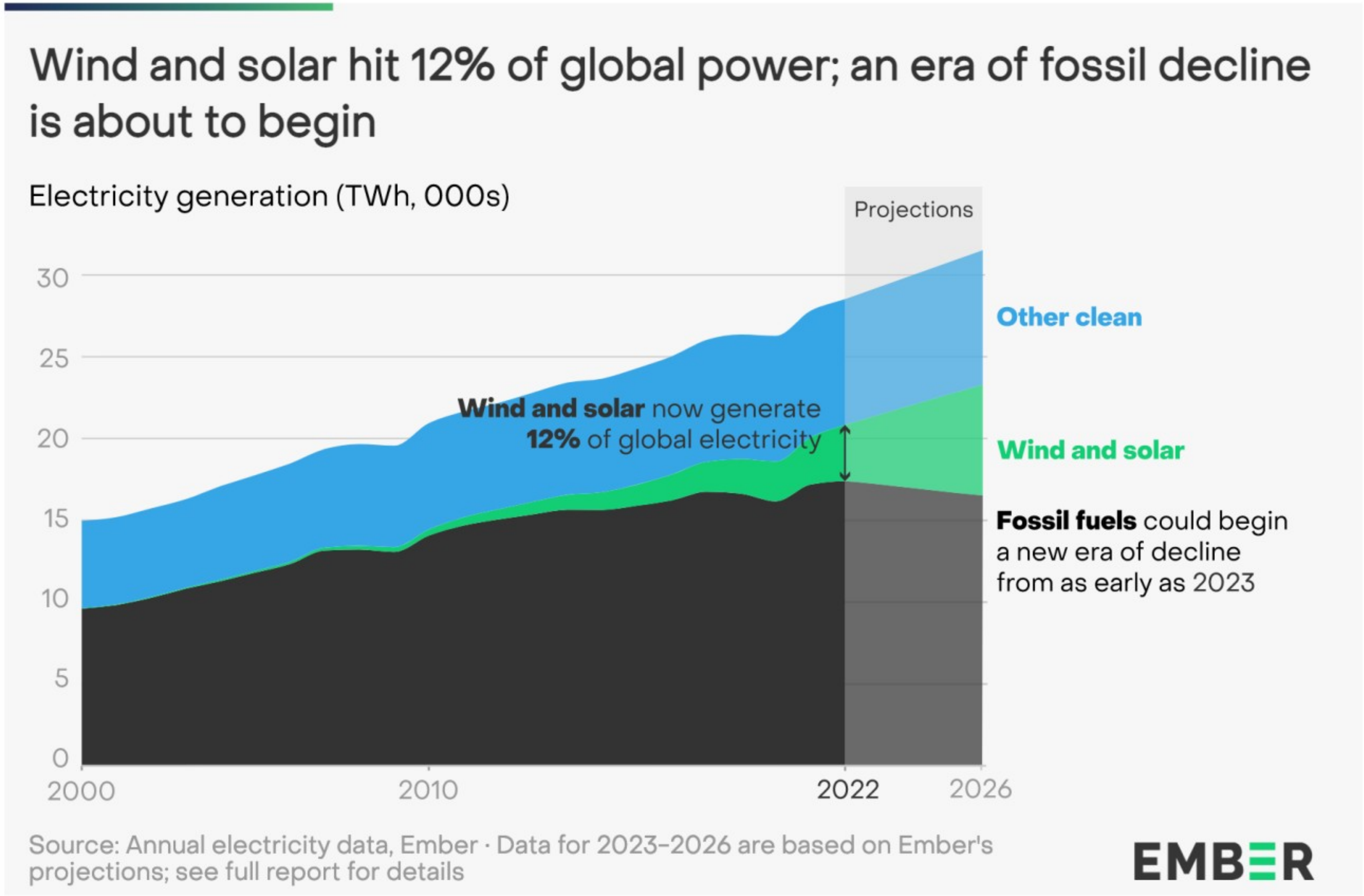
Share in electricity generation

Share of final energy demand

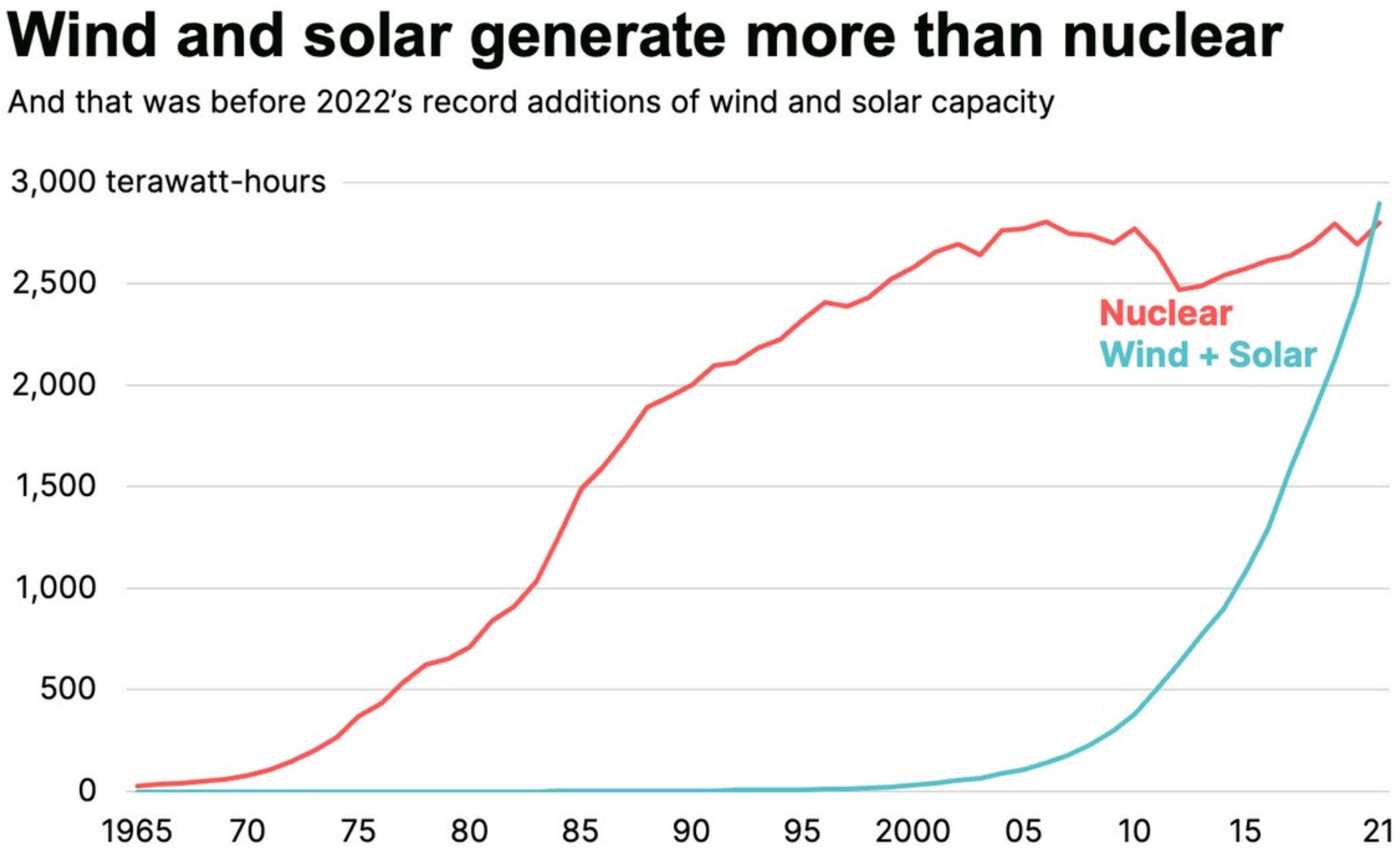
Renewables overtook fossil fuels as EU's main power source in 2020



Global power generation

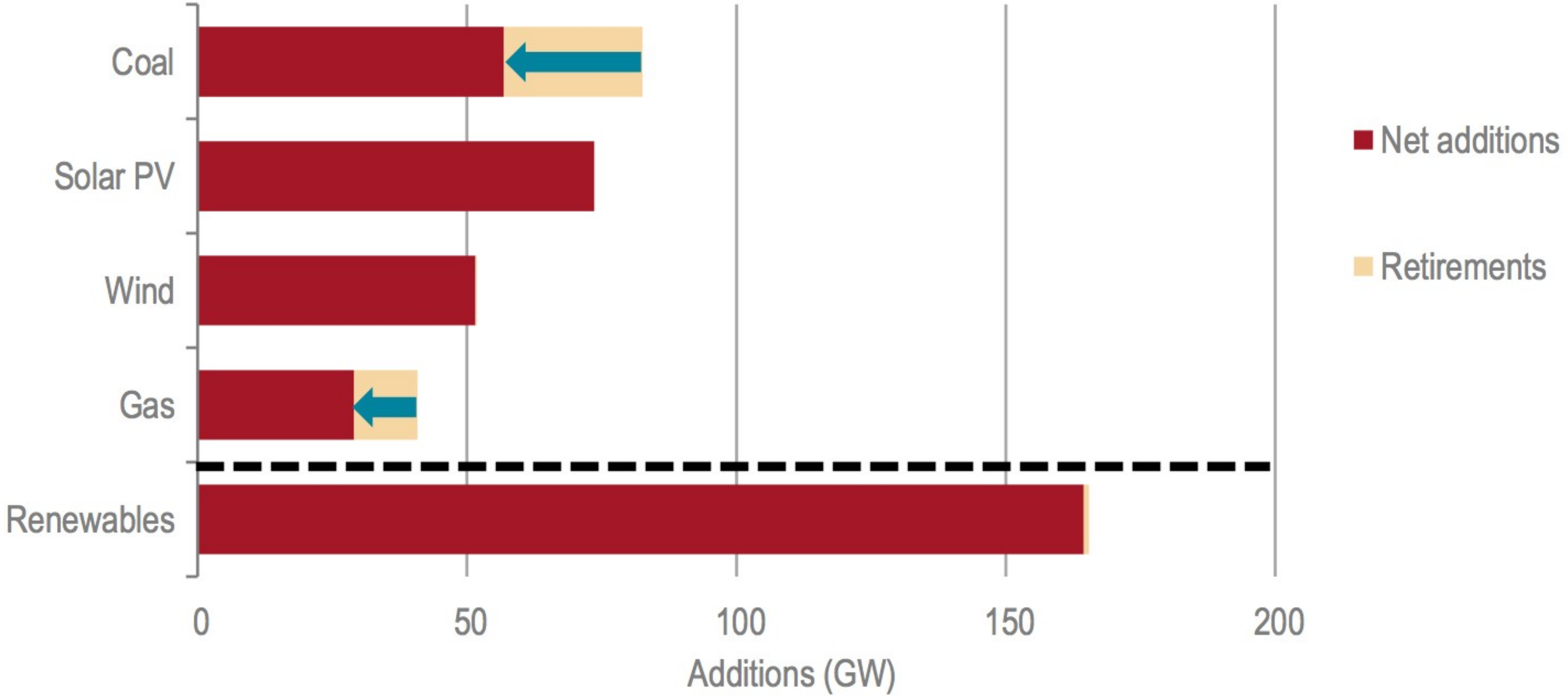


Global generation by wind, solar and nuclear



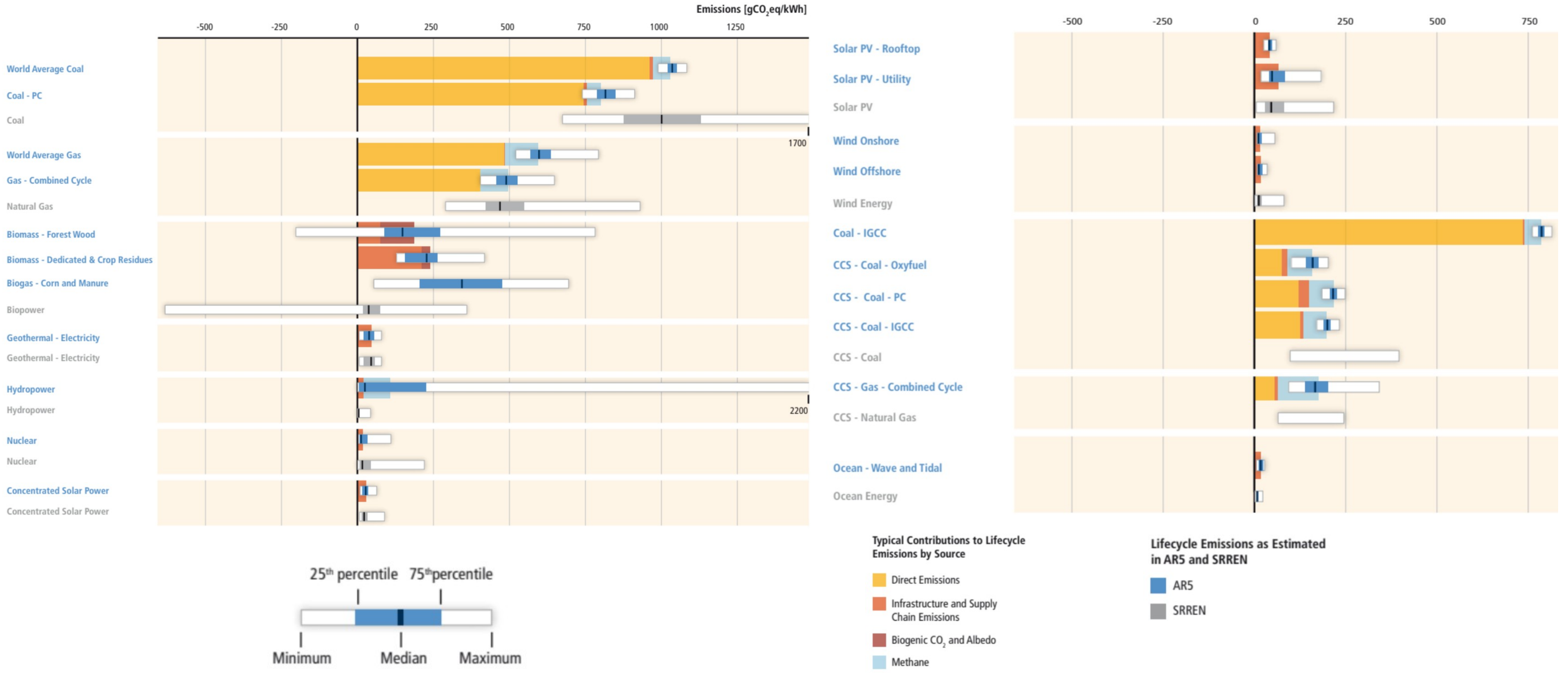
Sources: Nat Bullard, BP Statistical review of world energy 2022

Global electricity capacity addition



Source: Renewables 2017, IEA

Benefits of renewables (1): carbon footprint



Source: IPCC AR5 WG3, 2018

don't time to answer it in class, can be done at home

Question

If the life cycle emission combined cycle gas turbine are 500kg$_{CO2}$/MWh and those of coal power plant are 1000kg$_{CO2}$/MWh (cfr previous slides), which percentage of gas leakage would bring the carbon footprint of the gas power plant to the level of the coal power plant?

NB: to simplify, we can assume that natural gas is composed exclusively of methane. The 20-years Global Warming Potential of methane is given in the table below.

half life

Species	Lifetime (Years)	Radiative Efficiency (W m^{-2} ppb^{-1})	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000		
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2823 ± 1060	3531 ± 1385
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	78,175 ± 29,402	92,888 ± 36,534
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	146,670 ± 53,318	181,408 ± 71,365
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7660 ± 2464	9055 ± 3128		

le GWp diminue avec le temps car le gaz se désagrège au fur et a mesure du temps. Le lifetime c'est le half life

Source: IPCC AR6 WG1, 2021, Table 7.15

Current debate on leakage rates

Jamie Henn @jamieclimate · Oct 20, 2020 ···

If 3.2% of methane leaks during production, it makes **gas** worse than coal for the climate.

A study found the **leakage rate** in the Permian Basin, the largest oil & **gas** field in the US, is 3.7%.

Gas is a bridge...to hell.

insideclimatenews.org

Super-Polluting Methane Emissions Twice Federal Estimates in Permia...

Methane emissions from the Permian basin of West Texas and southeastern New Mexico, one of the largest oil-producing regions in ...

Matt McCarville @Matt_McCarville · Oct 15, 2019 ···

The overall U.S. methane leakage rate, from shale gas, which includes leaks from drilling and from pipe transmission and distribution to electric power plants, industrial facilities, homes, and other buildings, may be ~3.5% (@howarth_cornell, 2019). 3/11

1 1

The New York Times

Leaks Can Make Natural Gas as Bad for the Climate as Coal, a Study Says

The bottom line: If gas leaks, even a little, "it's as bad as coal," explains RMI's Deborah Gordon, "It can't be considered a good bridge, or substitute."

Kees van der Leun @Sustainable2050 · Jun 21, 2018 ···

Since methane is a much stronger greenhouse **gas** than CO2, such a 2.3% **leakage rate** would mean natural **gas** loses roughly half of its greenhouse **gas** advantage over coal.

> **Jilles van den Beukel** @JillesAppelscha · Jun 21, 2018
>
> New study published in Science estimates methane emissions from the U.S. oil and gas supply chain at 2.3% of US gas production (about 60% higher than estimated by the EPA). science.sciencemag.org/content/early/...

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Home / News / Energy & Environment / Gas / COP28: The new global crackdown on climate-wrecker methane

COP28: The new global crackdown on climate-wrecker methane

By Nikolaus J. Kurmayer | Euractiv.com Est. 5min Dec 3, 2023 (updated: Dec 4, 2023)

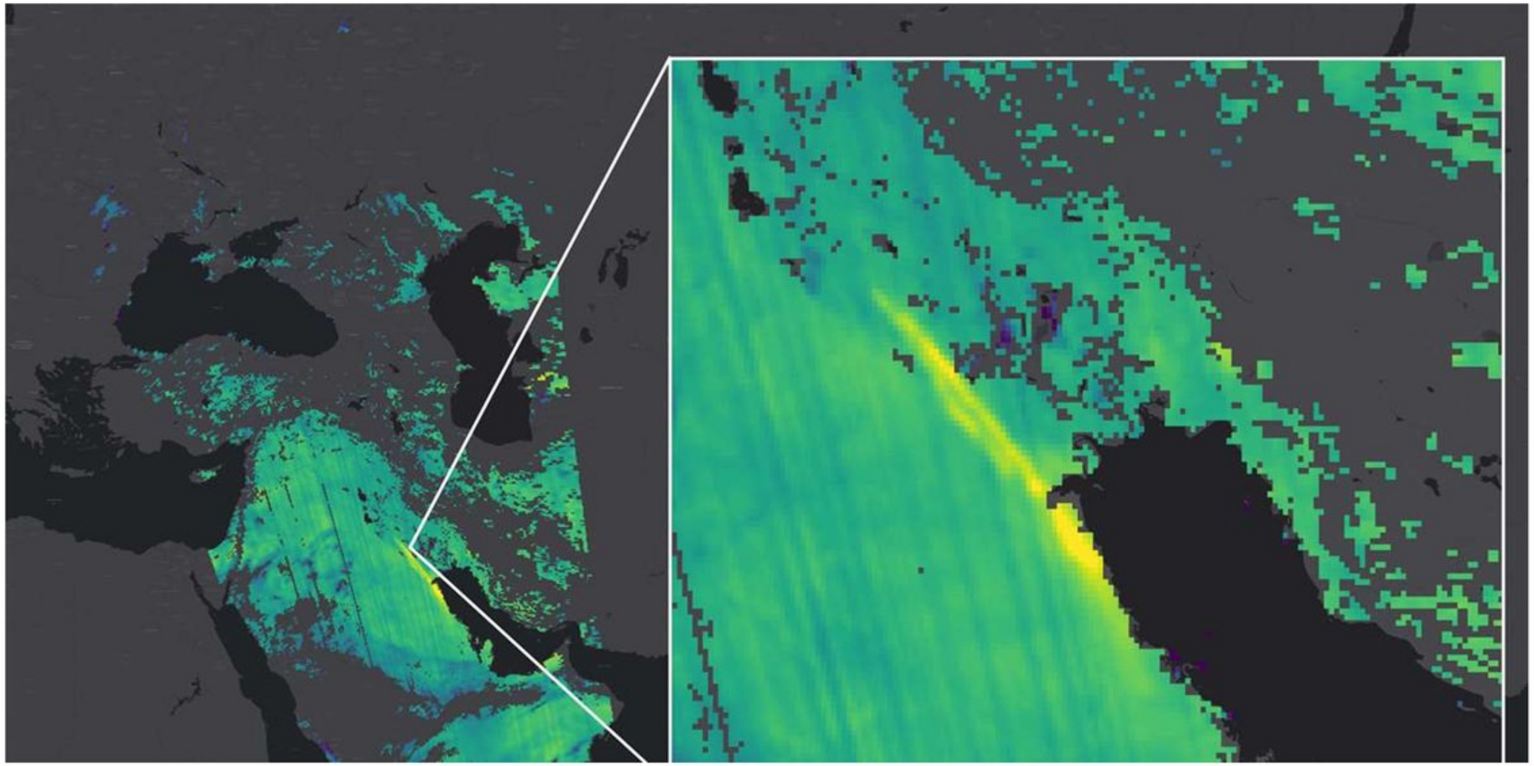
Energy Post @Energy_Post · Oct 30, 2023 ···

Even 0.2% **methane leakage** can make gas dirtier than coal: Texas LNG exported to China. Use the publicly available calculator, input site specific data go.shr.lc/3QhnQ9N #**methane** #gas #LNG #coal #**leakage** #US #emissions #GHG #regulations

Current debate on leakage rates

It is not just CO_2 that needs monitoring

Fugitive methane emissions complicate climate goals (and company reporting too)



January 2023

101

Source:
Kayrros

NAT BULLARD

Benefits of renewables (2): worldwide potential

There is enough technical potential for renewables to provide multiple times the current primary energy consumption (~600Ej)

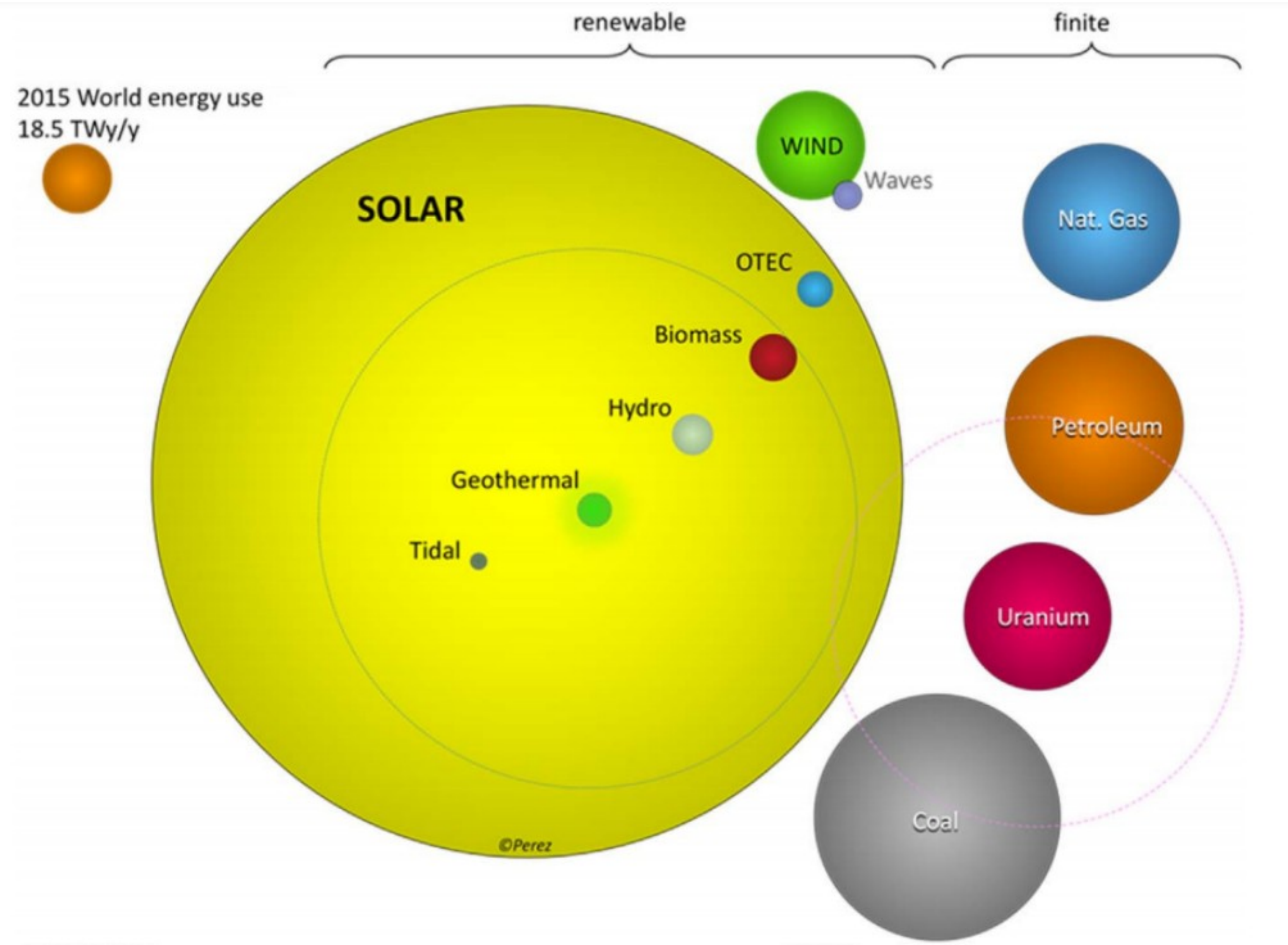
However, the estimates vary in a broad range

Published estimes for RE global technical potential (in Ej)

Study and year of estimate	Solar	Wind	Ocean	Hydro	Biomass	Geothermal	
						Electricity	Heat
Hafele (1981) ('*realizable' potential*)	NA	95 (*32*)	33 (*16*)	95 (*47*)	189 (*161*)	3.2 (*3.2*)	47 (*16*)
Lightfoot/Green (2002) (*range of values*)	163 (*118–206*)	72 (*48–72*)	0 (*1.8–3.6*)	19 (*16–19*)	539 (*373–772*)	1.5 (*1.5*)	NA (*NA*)
Gross et al. (2003)	43–144	72–144[a]	7–14[b]	NA	29–90	NA	14–144[c]
Sims et al. (2007)	1650	600	7	62	250	NA	5000[c]
Field et al. (2008)	NA	NA	NA	NA	27	NA	NA
Resch et al. (2008)	1600	600	NA	50	250	NA	5000[c]
Klimenko et al. (2009) ('*economic' potential*)	2592 (*19*)	191 (*8.6*)	22 (*2.2*)	54 (*29*)	NA (*NA*)	22 (*3.6*)	NA (*NA*)
Cho (2010)	>1577	631	NA	50	284	NA	120
Tomabechi (2010)[d]	1600	700	11	59	200	NA	310,000[c]
WEC (2010)	NA	NA	7.6[b]	57.4	50–1500	1.1–4.4	140
All studies range	118–2592	48–600	1.8–33	50–95	27–1500	1.1–22	14–310,000
Earth energy flows	3,900,000	28,400	700	130–160	3000	1300	

Source: [14,18,25–33].
NA: not available.
[a] Onshore only.
[b] Wave only.
[c] Includes both electricity and direct heat.
[d] 'Usable maximum'.

Benefits of renewables (2): worldwide potential

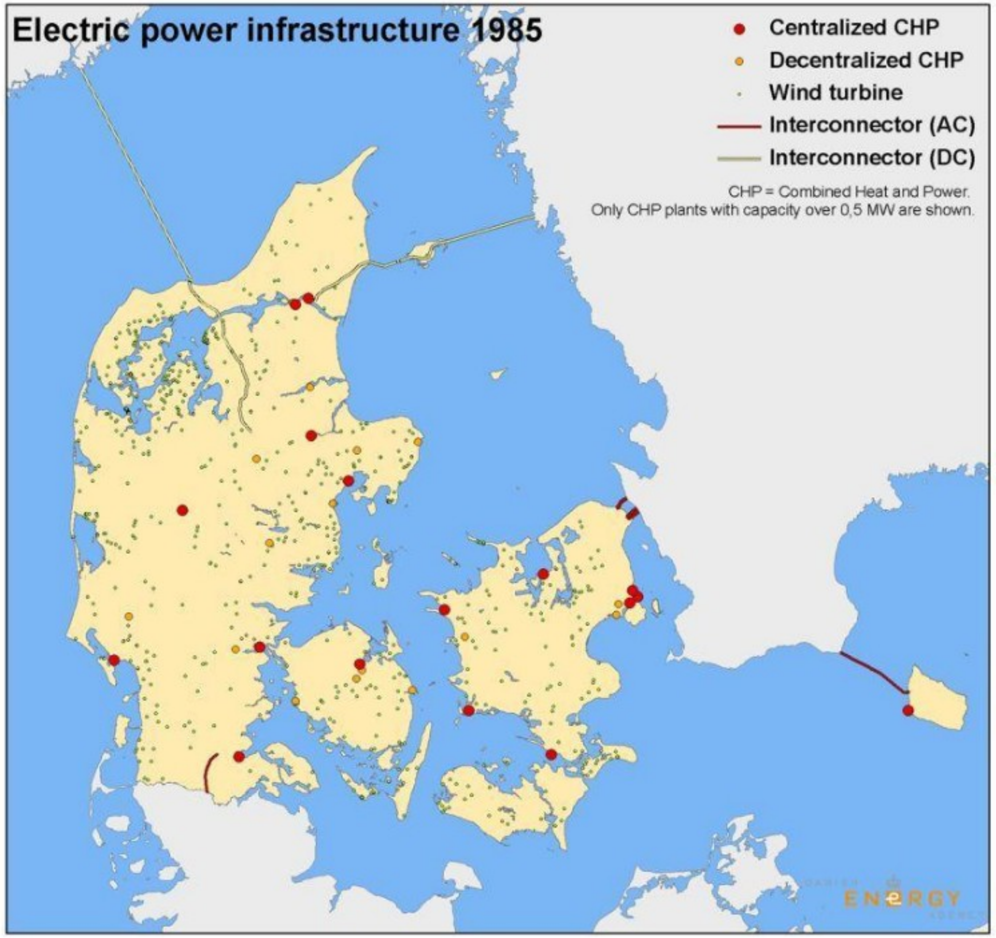


Source: Perez et al, Applied Policy, 2016

Benefits of renewables (2): Worldwide potential

- Careful with potentials! They are only estimates and are hard to evaluate.
- Example of the 2009 influential book ”Energy without the hot air” by David MacKay:
  - The book uses an estimate of 53 PTWh for the wind potential
  - The solar PV potential is discarded because of its excessive price
  - The book concludes that the renewable potential is insufficient for a ”post-European consumption” of 80 kWh/pers/day.
- However:
  - Only 8 years later, NREL re-assessed the global wind potential and obtained a number of 875 PWh, 16 times higher than MacKay’s estimate. (source: NREL, An improved global wind resource estimate for integrated assessment models, 2017)
  - The potential for solar is known to be orders of magnitude higher than the demand
  - These difference are explained by technical progress, more refined estimates, costs declines, ...
  - They completely invalidate the 2009 conclusions

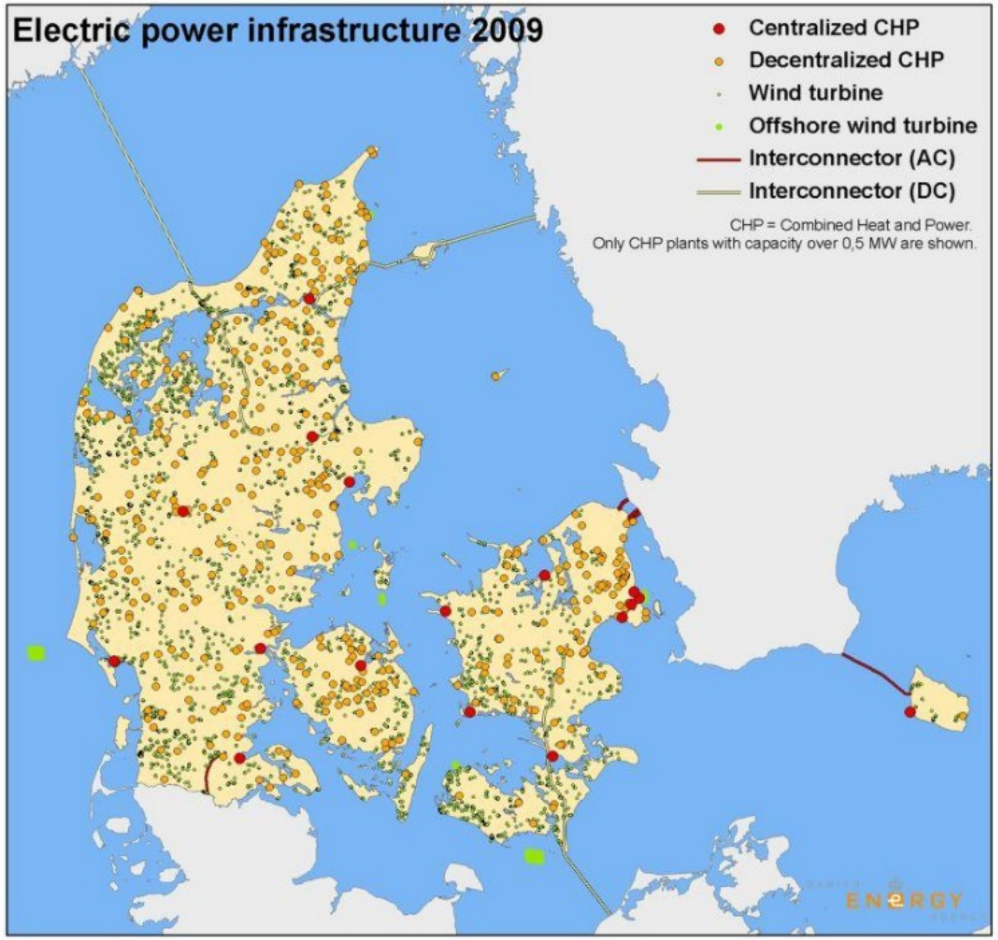
Benefits of renewables (3): Diversification



Denmark:

- Energy transition based on:
  - Insulation of homes
  - CHP and district heating
  - Wind power
- Results (from 1990 to 2020):
  - -15% primary energy consumption
  - -50% CO2 emissions
- The country is now a key player in the wind industry

Benefits of renewables (3): Diversification



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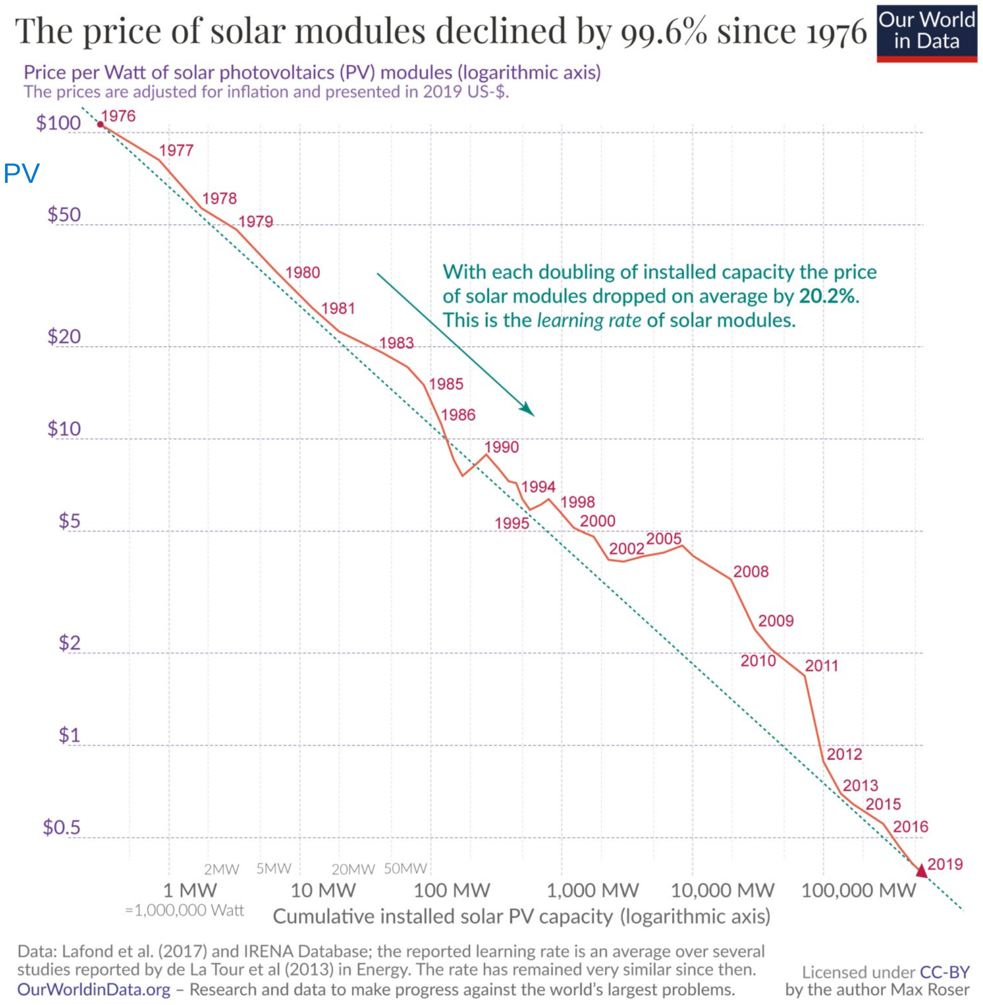
LIÈGE université

Benefits of renewables (4): Learning curve

price of PV



power installed of PV

We can build the learning curve by plotting the production costs as a function of the cumulated installed capacity

The learning rate is usually defined as the percentage change in costs for each doubling in capacity

If the learning curve is approximated by an exponential (Wright's model), we can write:

$$C = K \cdot Cap^{n}$$

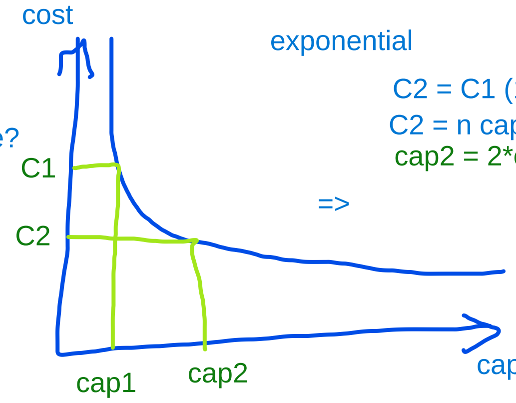
The exponent *n* can be expressed as:

phi is the learning rate. How much move the price if we double the capacity

$$n = \frac{\log(1-\varphi)}{\log(2)}$$

φ is the learning rate: at every doubling of the installed capacity, the unit costs decreases by $1-\varphi$

capacity double, how move the price?

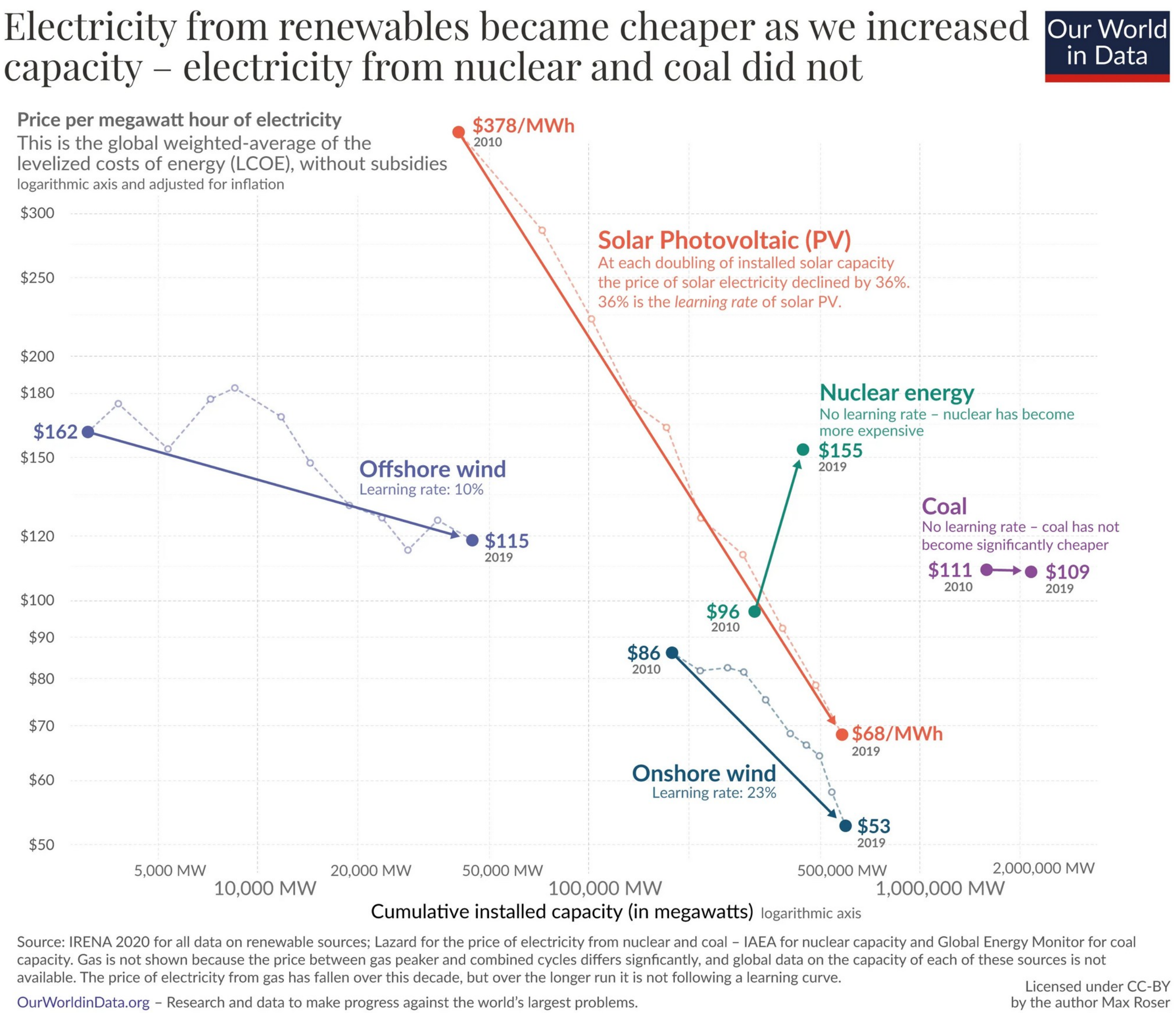


exponential

C2 = C1 (1 - phi)
C2 = n cap2**n
cap2 = 2*cap1

=>

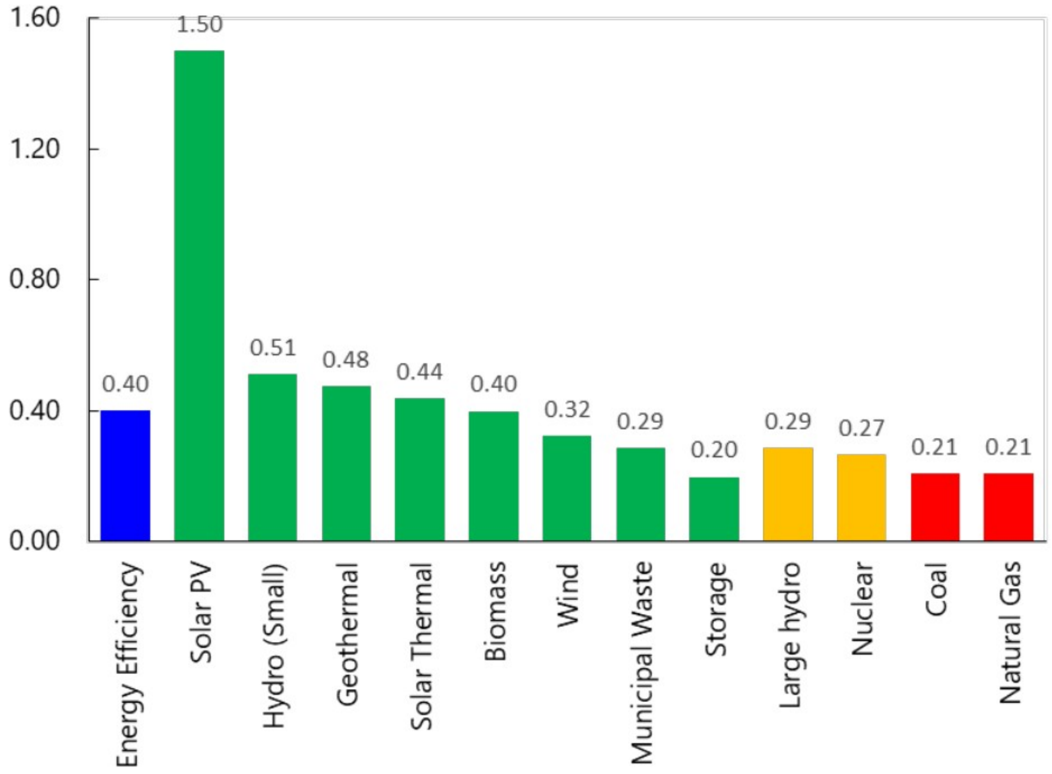
Benefits of renewables (4): Learning curve



Nuclear grow because more and more security and we don't develop a lot in Eu so we loose experimence

Benefits of renewables (5): Jobs and macroeconomic insulation

- Renewables are more work-intensive than conventional generation technologies
- In jobs-years per GWh:

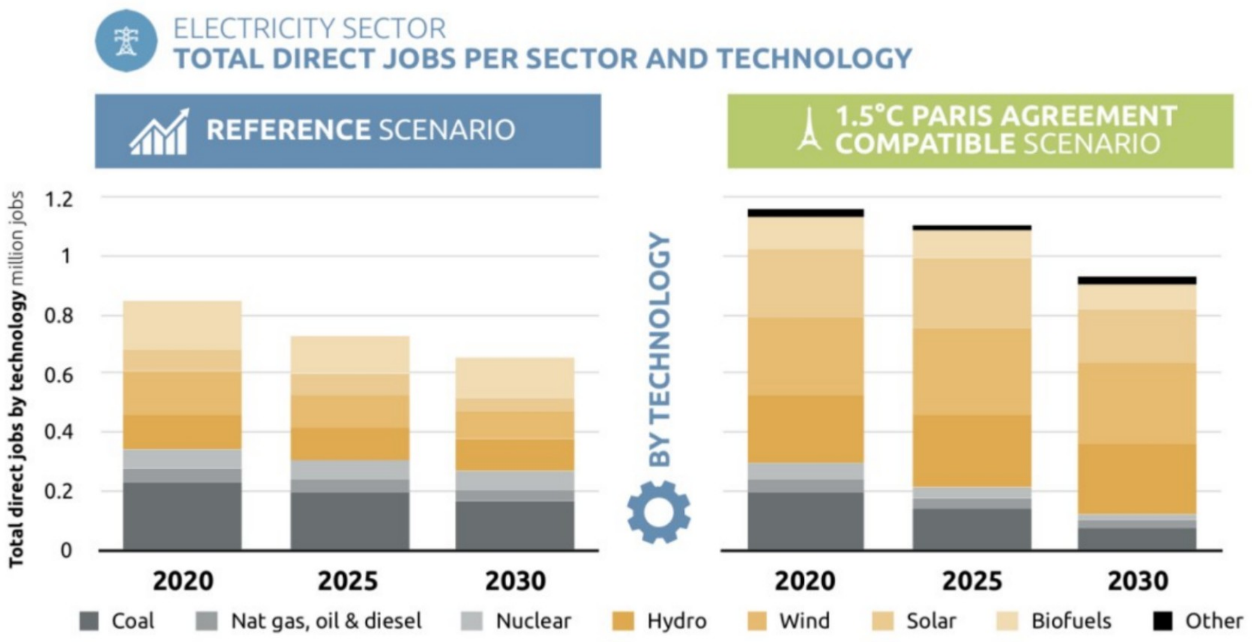


Source: Kammen, Wei, and Patadia (2010)

Benefits of renewables (5): Jobs and macroeconomic insulation

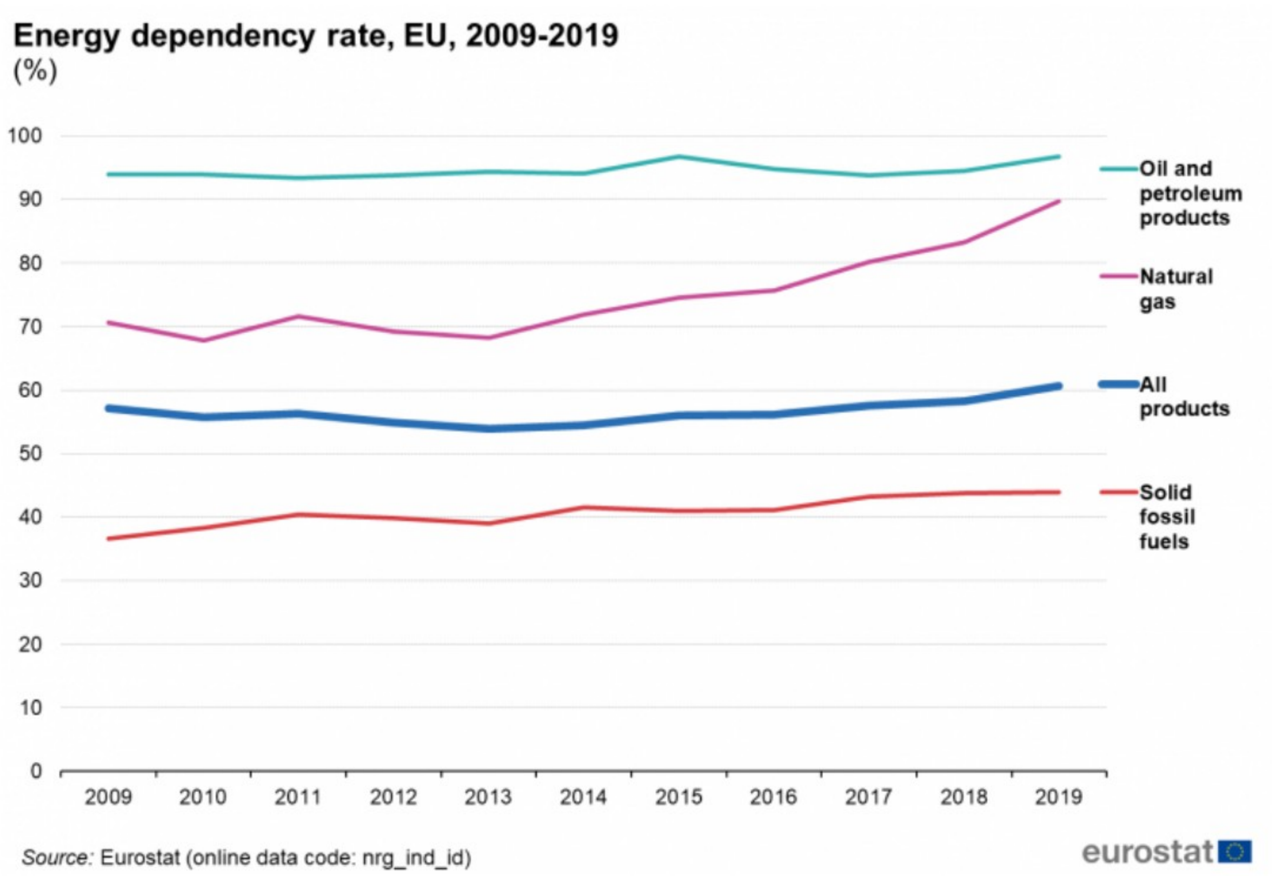
Total direct jobs per employment sector and total direct jobs per generation technology for the reference scenario (graphs on left) and the 1.5°C Paris Agreement compatible scenario (graphs on right) for the EU electricity supply sector.

Note: ‘other’ comprises geothermal, marine and waste.



Source: Climate Action Tracker, 2018

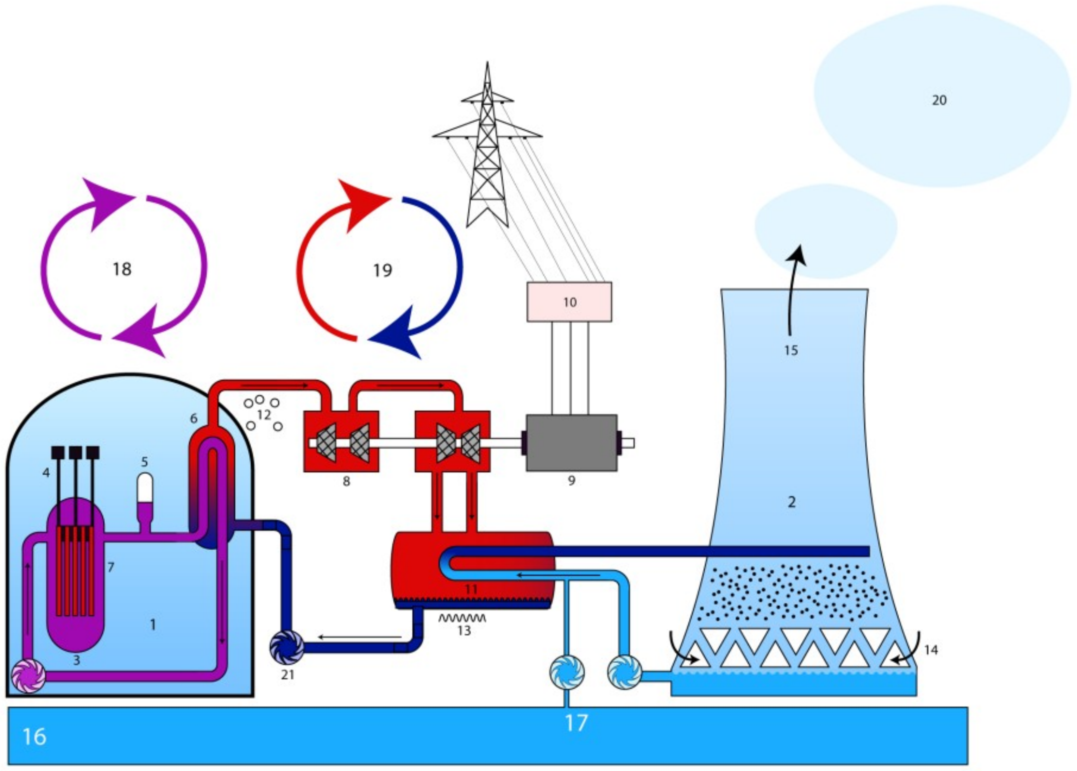
Benefits of renewables (5): Jobs and macroeconomic insulation



a lot of importation

- More than half (60.7 %) of the EU's gross available energy in 2019 came from imported fossil fuel sources.
- EU's energy import bill reached 331 billion EUR in 2018, more than 2% of EU GDP

Benefits of renewables (6): Water

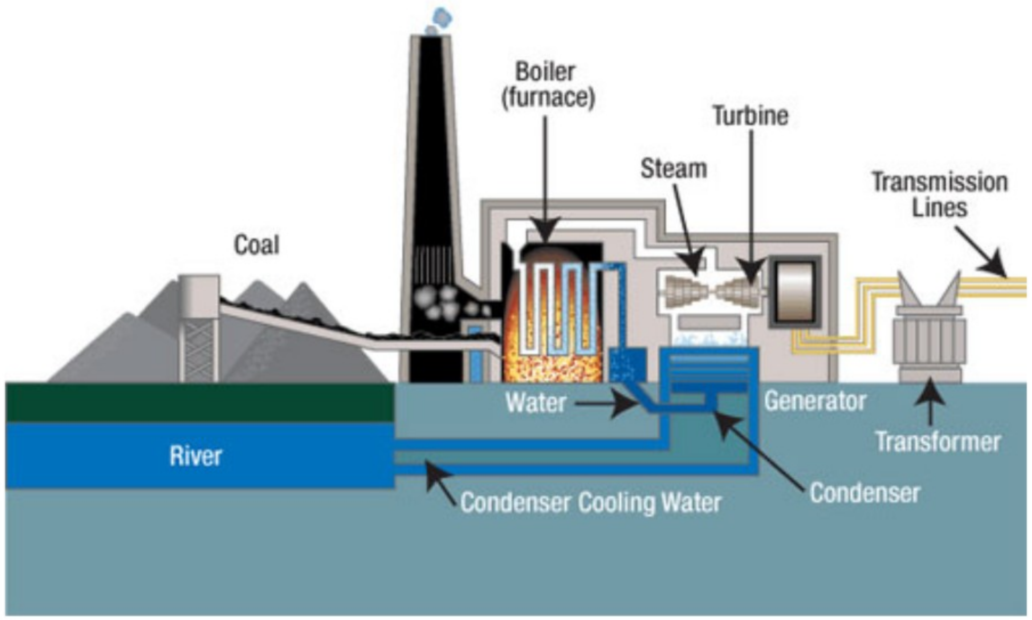


In case of indirect, wet cooling:

- Significant water consumption
- Evaporated in the cooling tower

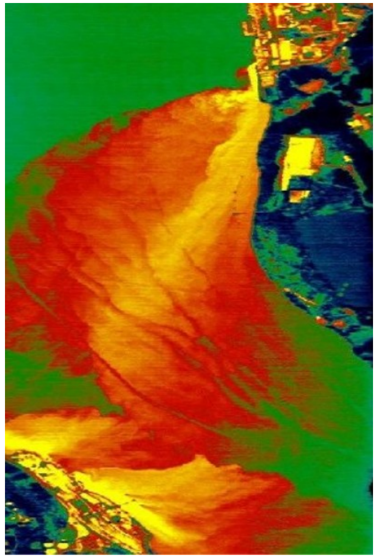
In summer sometimes we need to decrease the production of the power plant because there is not enough water (not in Belgium but in France)

Benefits of renewables (6): Water



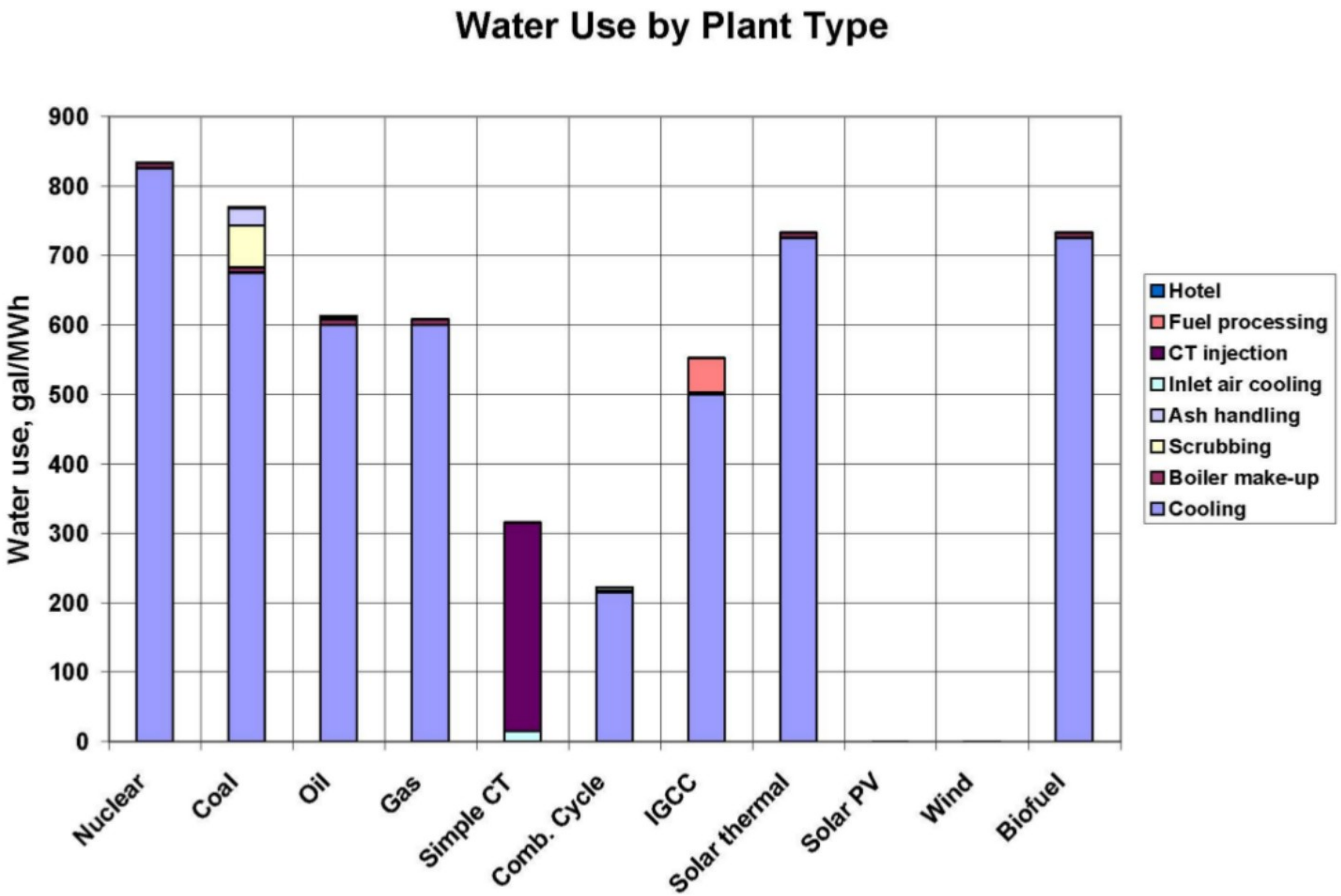
In case of direct cooling:

- High thermal pollution
- High water withdrawal
- But no water consumption



Thermal pollution in the Hudson River downstream of the Indian Point nuclear power plant, New York

Benefits of renewables (6): Water



Benefits of renewables (7): Accidents

- Large-scale technologies can cause huge and widespread damages
- Ex:
  - Chernobyl
  - Fukushima
  - BP spill in the gulf of Mexico
- Small scale often means less impact if something goes wrong

Benefits of renewables (8): Cost

How can we compare the cost of a gas power plant (high operation and fuel cost, low upfront investment cost) with a wind power plant (low operation cost, no fuel costs, high investment cost)?

1€ spent today does not have the same value as 1€ spent in 10 years. The future value F_k of an investment I_0 compounded (interest earns interest) annually for k years at a discount rate d is:

$$F_k = I_0(1+d)^k$$

To compare the costs, we will compare the annual costs (annuity). For a constant annuity A paid every year for n years to cover the initial investment I_0, we have:

$$\begin{aligned} I_0 = \sum_{k=1}^{N} A(1+d)^{-k} &= \frac{A}{(1+d)^N}\sum_{k=1}^{N}(1+d)^{N-k} = \frac{A}{(1+d)^N}\sum_{k=0}^{N-1}(1+d)^k \\ &= \frac{A\left[(1+d)^N - 1\right]}{d(1+d)^N} = A\frac{1-(1+d)^{-N}}{d} = \frac{A}{\psi} \end{aligned}$$

ψ is called the annuity factor. It allows to transform an initial investment into an annual costs paid during the whole duration of the projetct.

Benefits of renewables (8): Cost

A convenient indicator to compare the costs is the Levelized Cost of Energy (or Electricity). It corresponds to the total annual expenses per MWh of energy (or electricity) produced. It is obtained by dividing the annuity and all recurrent annual costs by the number of MWh produced each year.

The annual expenses are given by:

$$Cost_{annual} = I_0 \psi + \frac{C_f}{\bar{\eta}} \cdot E_{annual} + U_{fix} + u_{var} \cdot E_{annual}$$

- I_0 is the total investment cost of the plant and ψ is the annuity factor: $\psi = \frac{d}{1-(1+d)^{-N}}$
- C_f [€/MWh] is the levelized unit cost of fuel (if any).
- η is the yearly average plant efficiency
- U_{fix} [€/year] and u_{var} [€/MWh] are the levelized fixed and variable costs
- E_{annual} is the energy generated every year\item

E_{annual} can also be expressed as a function of the the rated power (P_i) and and the equivalent number of operation hours at rated power (τ). It can also be expressed as function of the capacity factor (CF), which the yearly fraction of running hours:

$$E_{annual} = P_i \cdot \tau = \frac{P_i \cdot 8760}{CF}$$

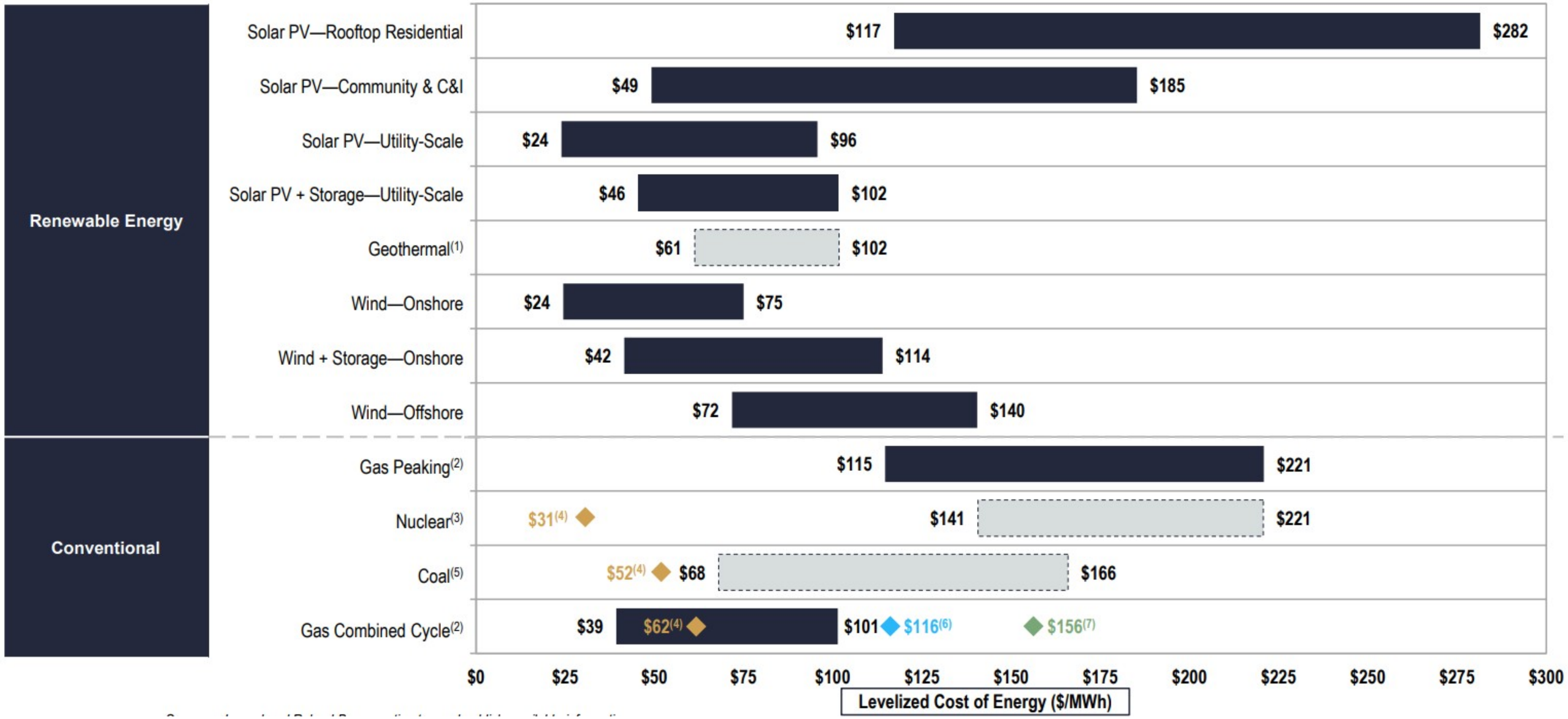
The LCOE is finally obtained by dividing the yearly expenses by the yearly energy production:

important concept

$$LCOE = \underbrace{\frac{I_0 \psi}{P_i \tau}}_{\text{CAPEX}} + \underbrace{\frac{C_f}{\bar{\eta}} + \frac{U_{fix}}{P_i \tau} + u_{var}}_{\text{OPEX}}$$

Benefits of renewables (8): Cost

In the past, renewables have been heavily subsidized. However, due to the rapidly falling prices of wind turbines and PV, some technologies are now more cost-effective than fossil-fuel or nuclear generation in most places in the world.
The plot below presents a recent estimates of the LCOE for various technologies.



Source: LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 16.0

Benefits of renewables (8): Cost

cost of electricity at home: 240 €/MWh

LCOE does not incorporate the externalities. Externalities are ”hidden costs”, consequence of the considered activity. They include for example the damages to the environment or the adverse health effects for nearby residents. It is not easy to quantify them, but they are obviously much lower for renewable technologies. The figure below provides a summary of different estimates from a meta-analysis.

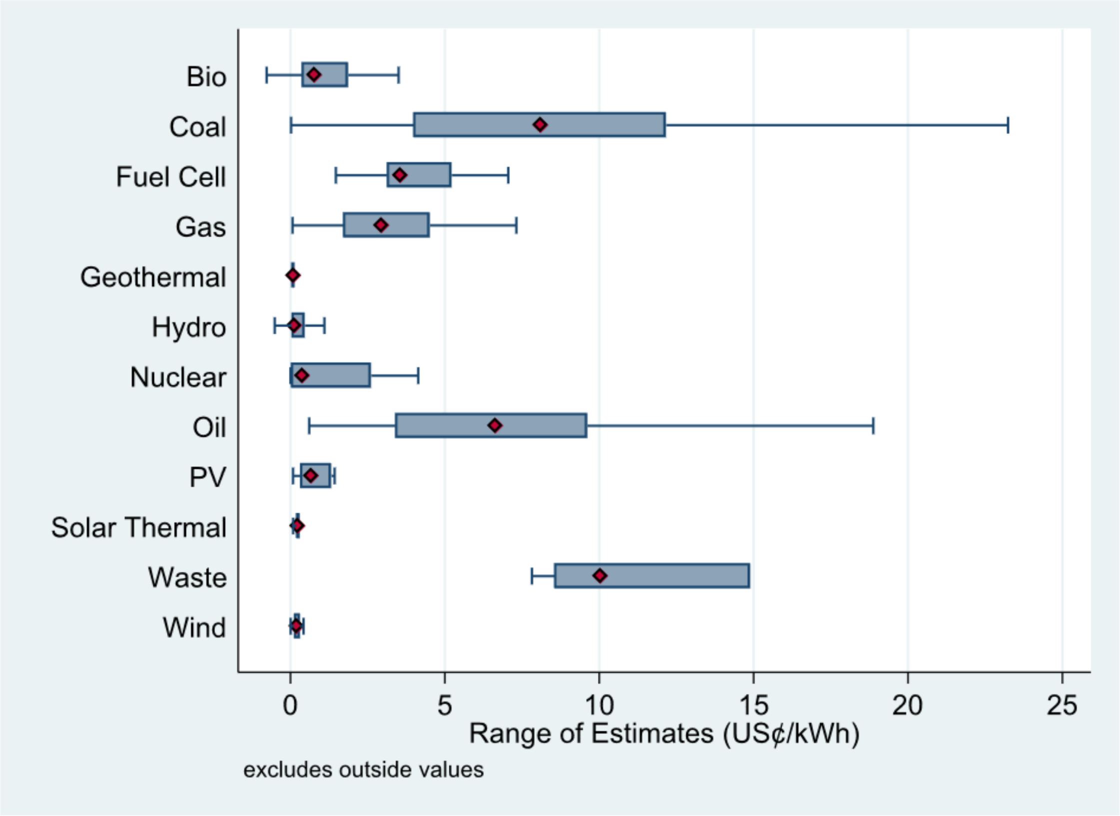


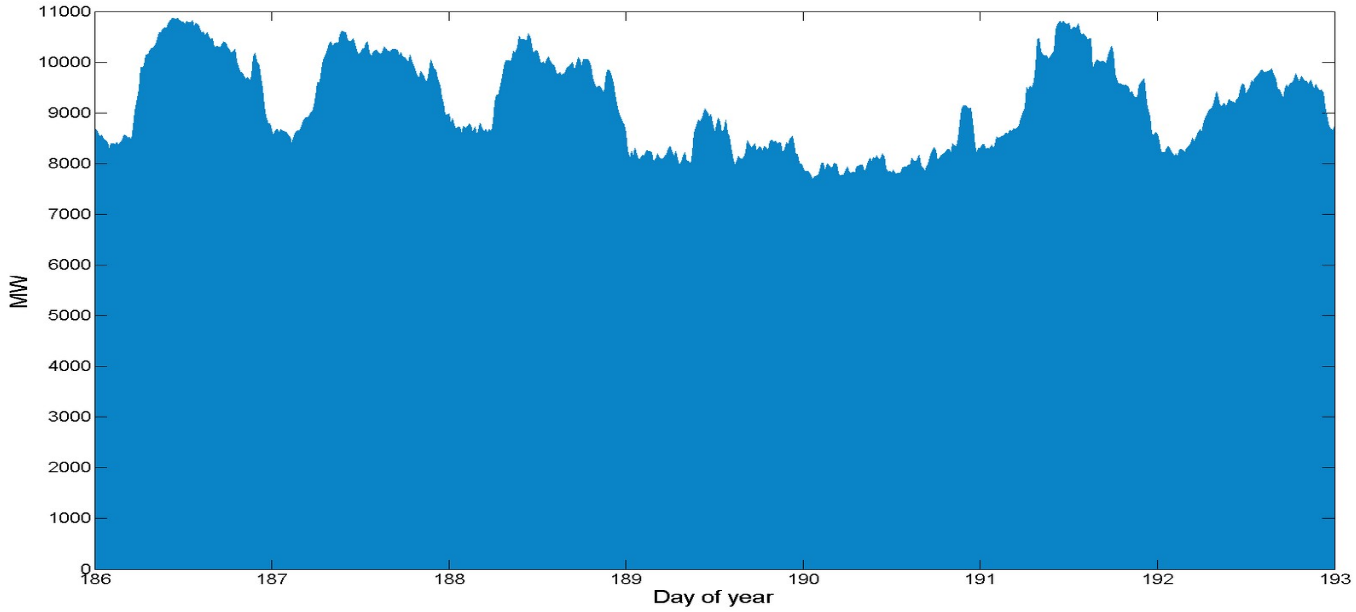
Fig. 2. The negative externalities associated with electricity supply (adjusted to US$2018, ¢/kWh). The estimates are for the externalities presented in Fig. 1, and air pollution and aesthetics (if estimated) are the most important in terms of cost. Low-carbon sources of electricity such as geothermal, solar thermal and solar PV, wind, hydro, and nuclear have the lowest negative externalities. The left end denotes minimum and the right end maximum in the box-and-whisker plots. The red dot means the median, and the left and right end of the box represent the first and third quartiles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

include OPEX and CAPEX but not cost internalities (voir ce que c'est sur internet)

Source: Sovacool et al., The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities, 2021

Disadvantages of renewables (1): Variability

Example: The Belgian demand and generation from July 6th to 12th, 2011



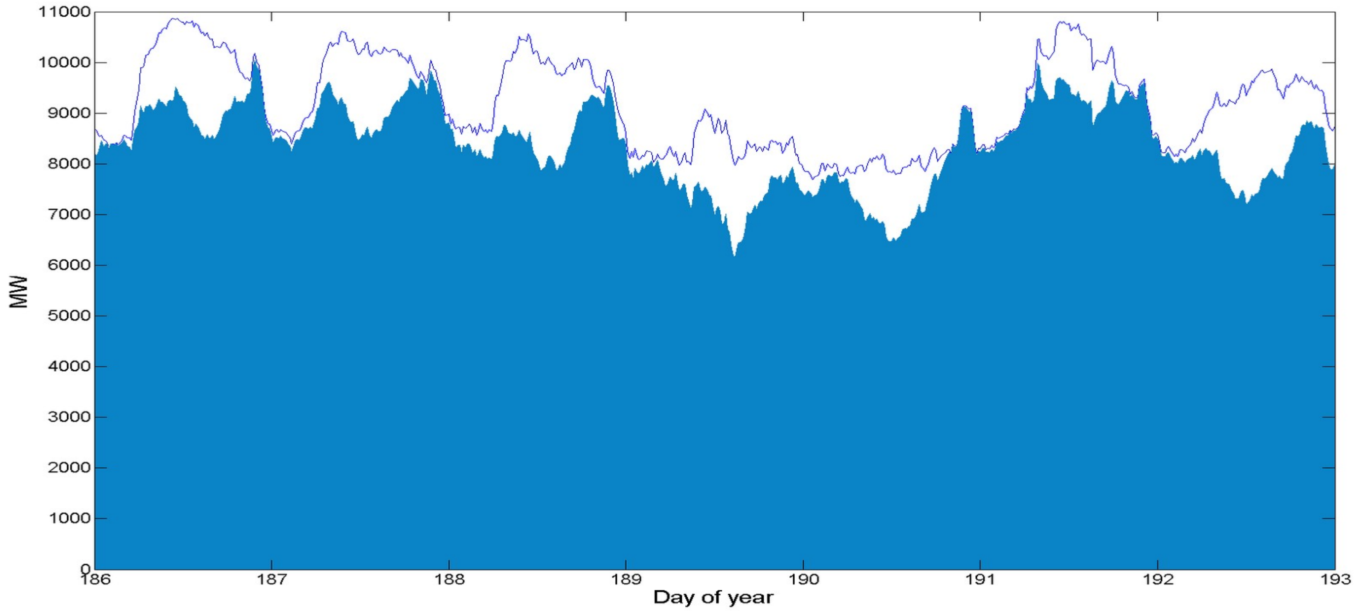
Eolien:

Photovoltaïque:

residual load is the demande - the renewable production

Disadvantages of renewables (1): Variability

Example: The Belgian demand and generation from July 6th to 12th, 2011



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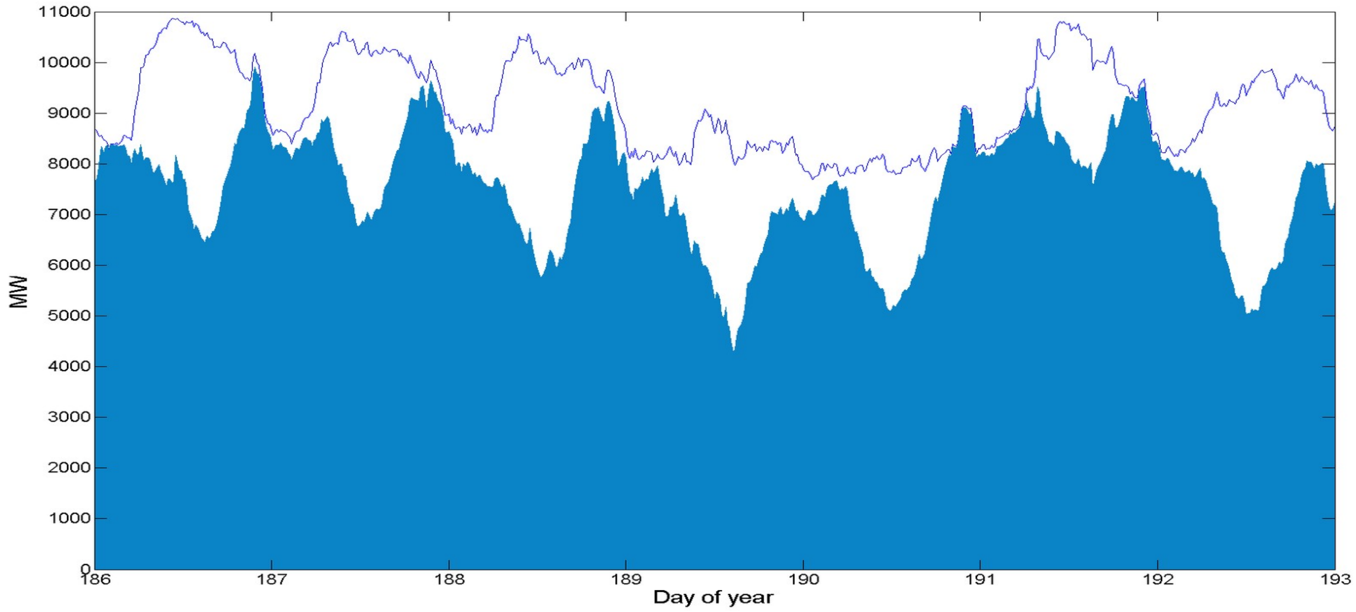

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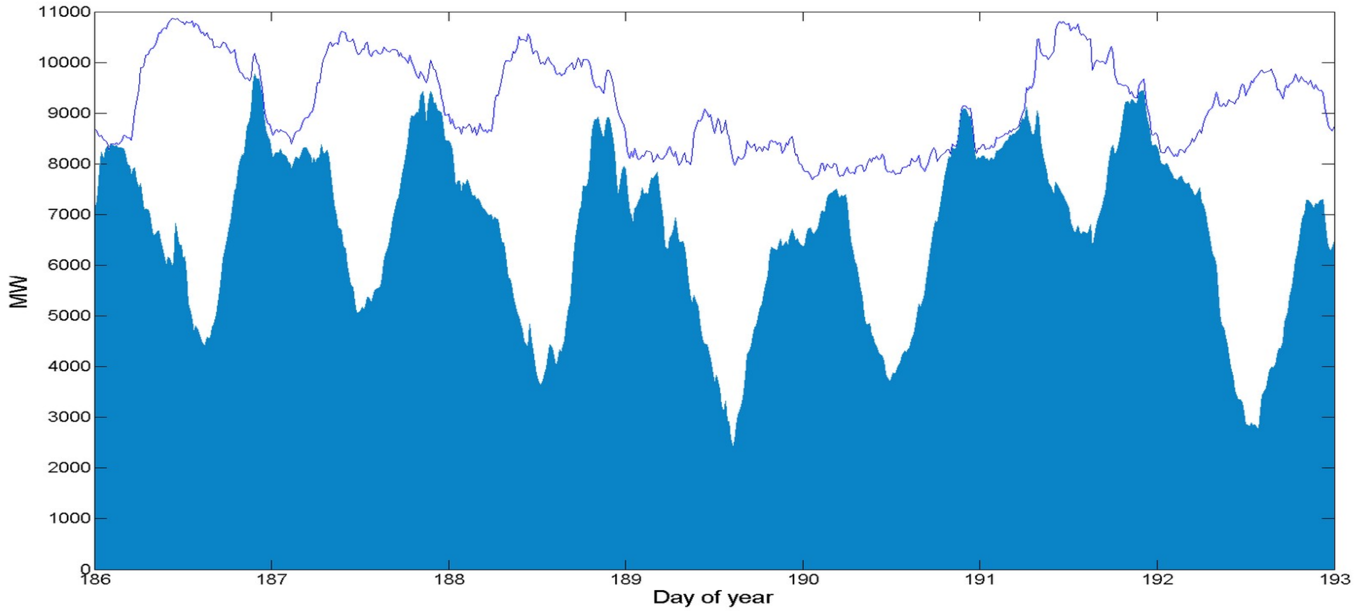

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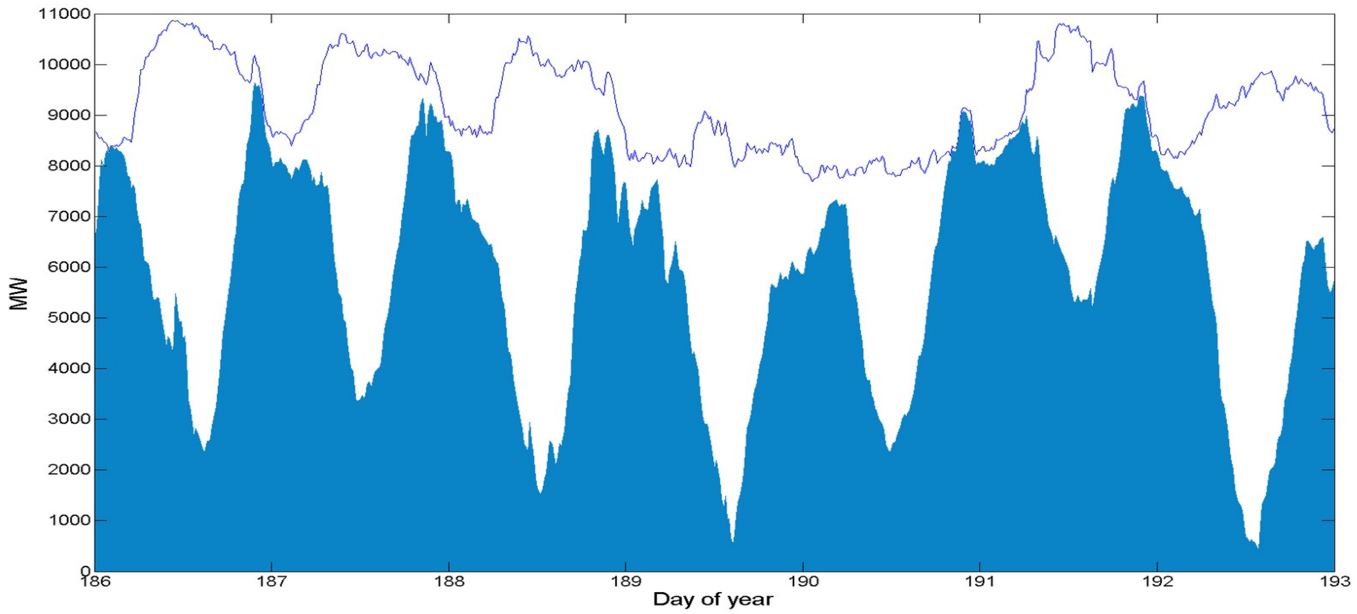


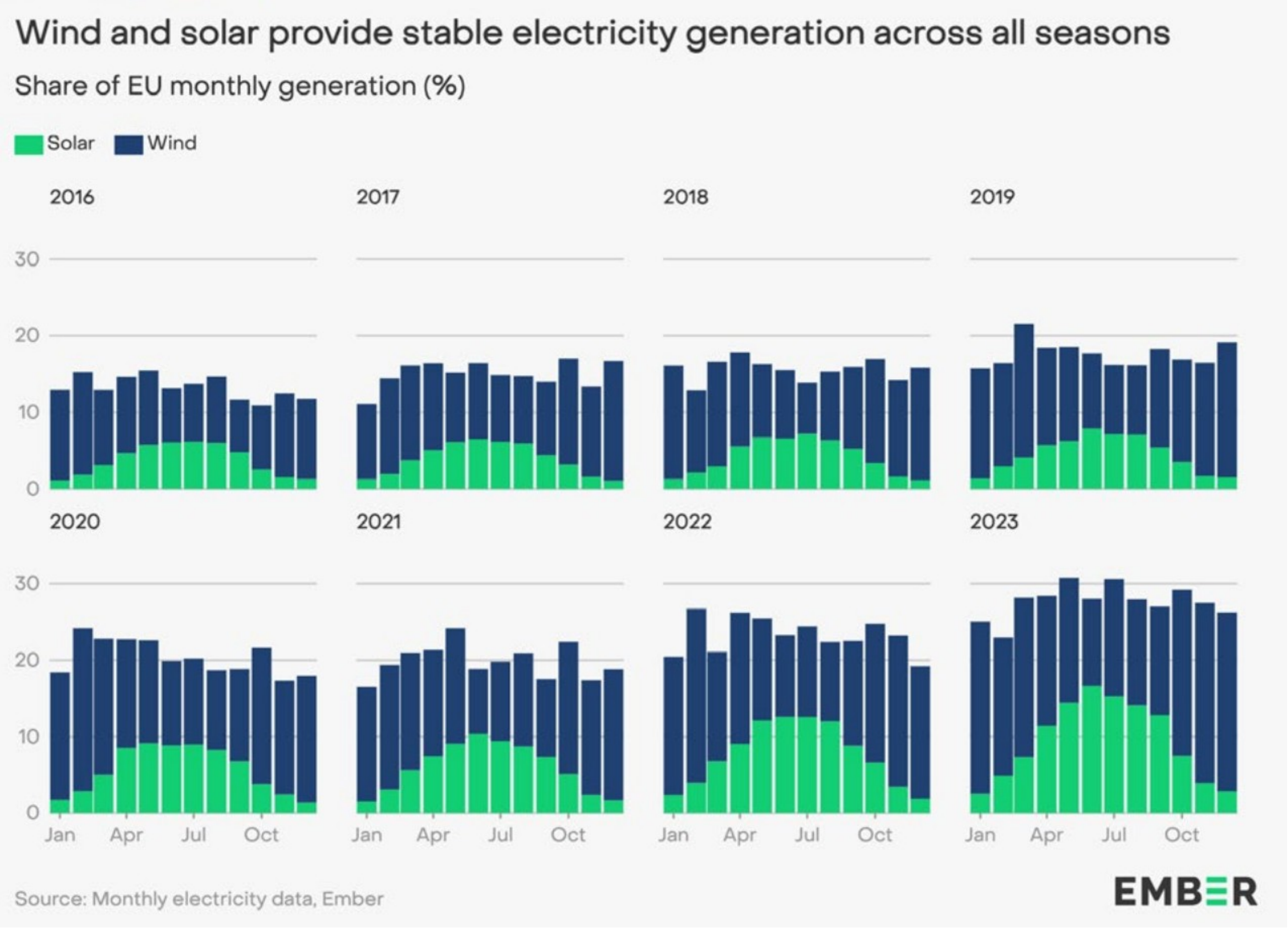
reaching time when the residual load is negative

Eolien:

Photovoltaïque:

Disadvantages of renewables (1): Variability

At the EU level, seasonal variability is high when considering solar alone.
However when combined with wind, renewable generation is more stable.



Disadvantages of renewables (2): Embedded energy

We will consider two concepts/metrics to evaluate the amount of energy required for the production of the renewable technologies themselves (e.g. the wind turbine)

- Energy return on investment (EROI, or energy return on energy invested, EROEI) is the ratio of energy returned from energy extraction and production activities compared to the energy invested in those energy gathering processes.

$$EROI = \frac{\text{lifetime energy output}}{\text{Embedded energy}}$$

eroi of oil decrease because before it was very cheap to extract it (from 100 to 50)

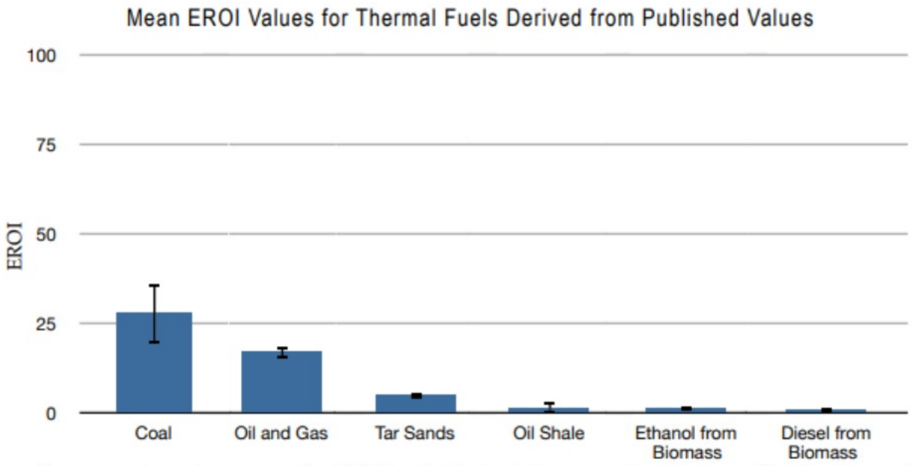
- Energy Payback Time (EPBT) is the time it takes for the system to generate the amount of energy equivalent to the primary energy or kWh equivalent that was used to produce the system itself.

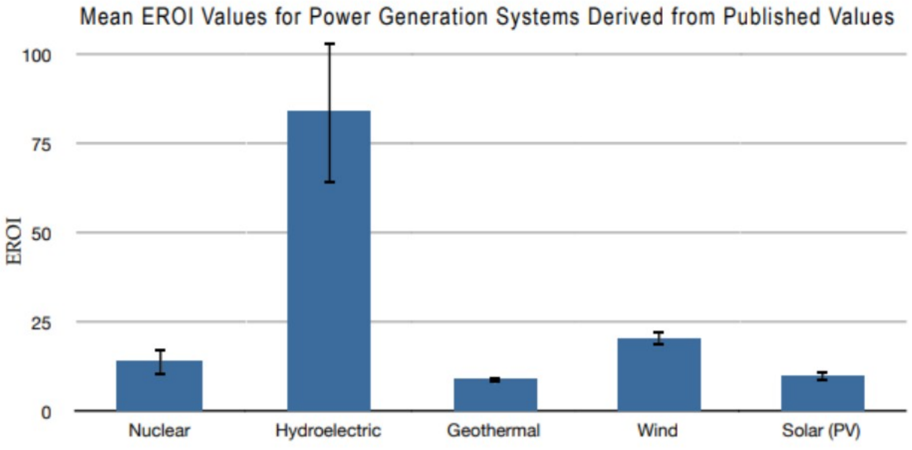
$$EPTB = \frac{\text{Embedded energy}}{\text{Annual energy generated}} = \frac{\text{lifetime}}{\text{EROI}}$$

Disadvantages of renewables (2): Embedded energy

Energy Return on Investment:

- EROI can be relatively low for renewable energy sources (typical ~10)
  - However, it increases in time in the case of renewables (technology improvements)
  - It decreases in time for fossil fuels (low-hanging fruits already taken)
- For biofuels, there are some cases in which it is lower than one! This bias can be created by poorly designed subsidiation schemes and is obviously problematic.



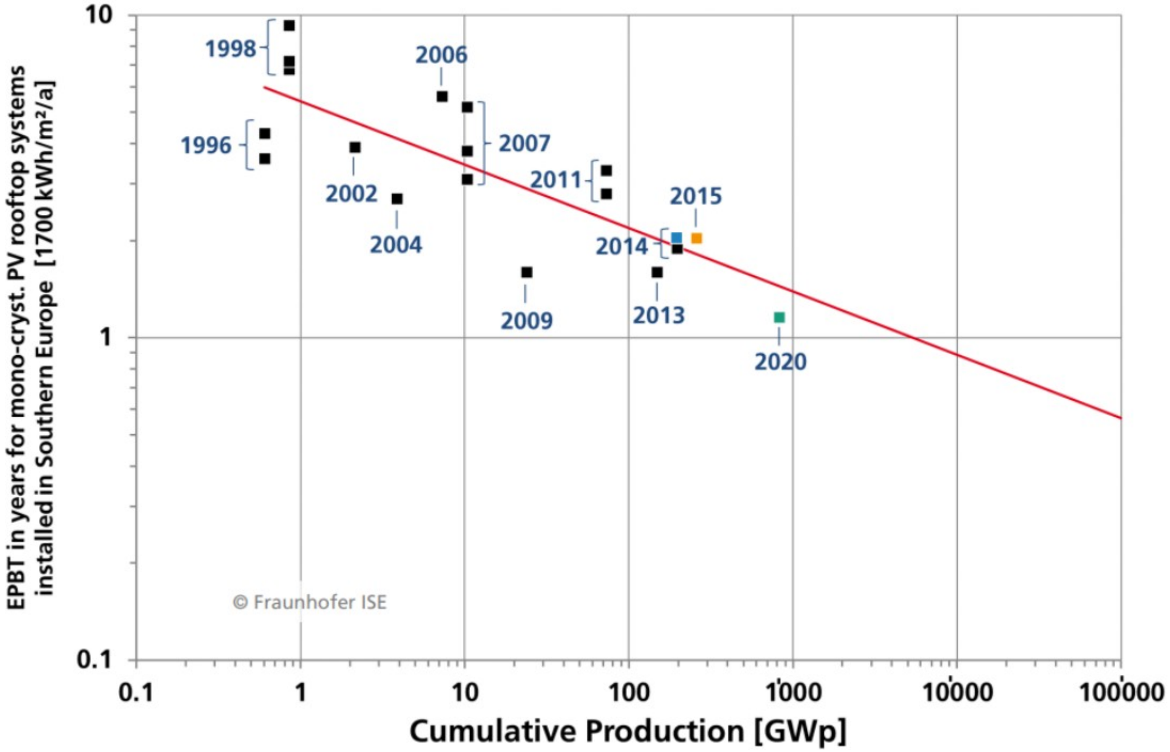


Source: Lambert et al, EROI of Global Energy Resources Preliminary Status and Trends, 2012

Disadvantages of renewables (2): Embedded energy

Energy payback time

- There is also a learning curve for the energy payback time!
- Example with solar PV:

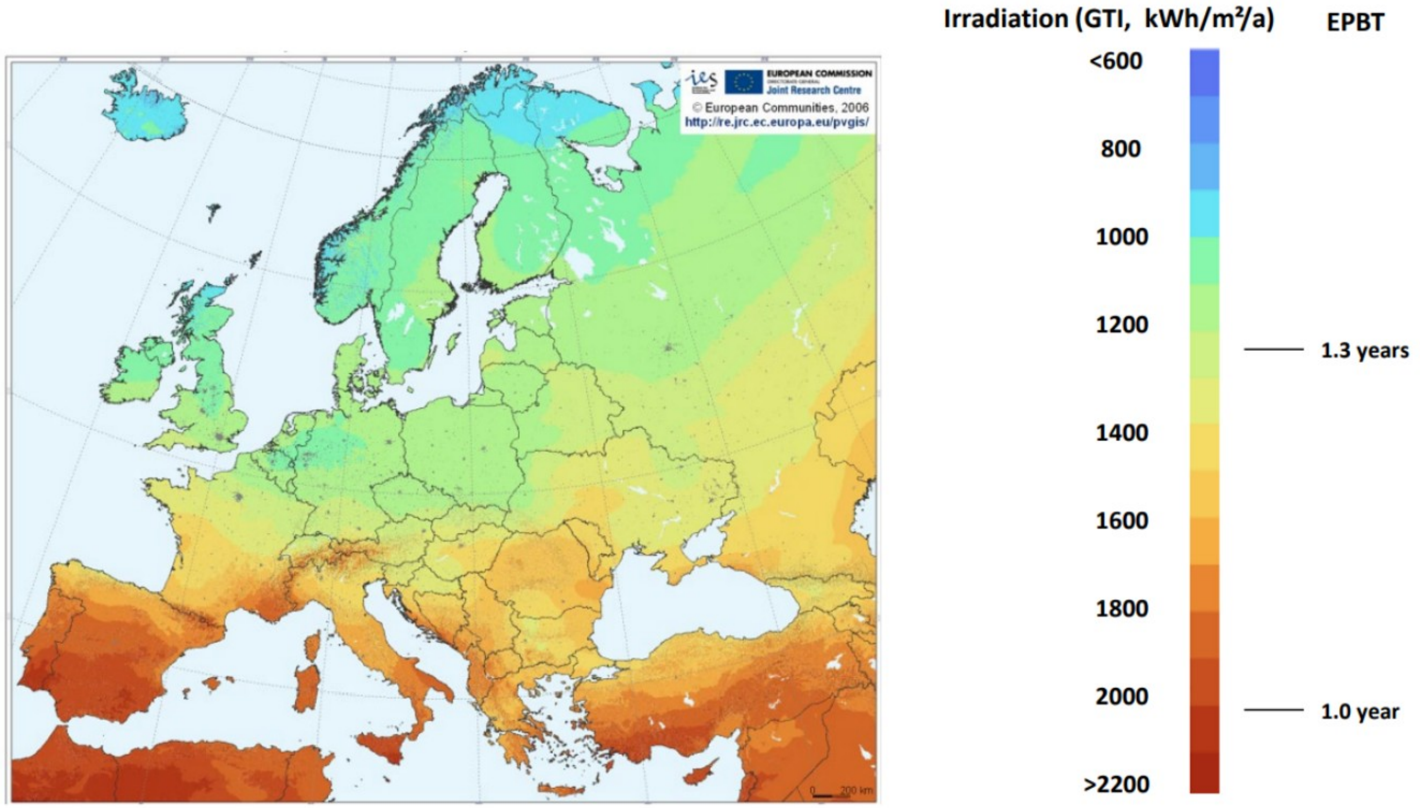


Source: Fraunhofer Institute for Solar Energy Systems, ISE, PV Report, 2021

Disadvantages of renewables (2): Embedded energy

Energy payback time

- Highly variable depending on the technology, the location, etc.
- Rule of thumb: 0.5 year for wind, 1 to 1.5 years for PV



Source: Fraunhofer Institute for Solar Energy Systems, ISE, PV Report, 2021

Disadvantages of renewables (3): Land use

- Most renewable energy sources ”consume” a significant amount of land.
- Exceptions: geothermal, hydro run-of-river
- Expansion potentials are limited by land usage, living areas, conservation areas; potential yearly energy yield at each site is also limited by weather conditions
- A good metrics for land usage is the power density. The **peak power density** (in Wp/m2) should not be confused with the **average power density** (in W/m2). The ratio between both is the **Capacity Factor** (CF)
- Land usage should also be considered at the light of alternative activities. For example, agriculture is compatible with wind turbines, and new concepts of agriculture with PV (”agrivoltaics”) are appearing.

Capacity factor: actual generation/ What the PV can produce if the PV produce their maximum

PV in spain: 90%
Winf offshore: 40-60%
Wind onshore: 20-30%

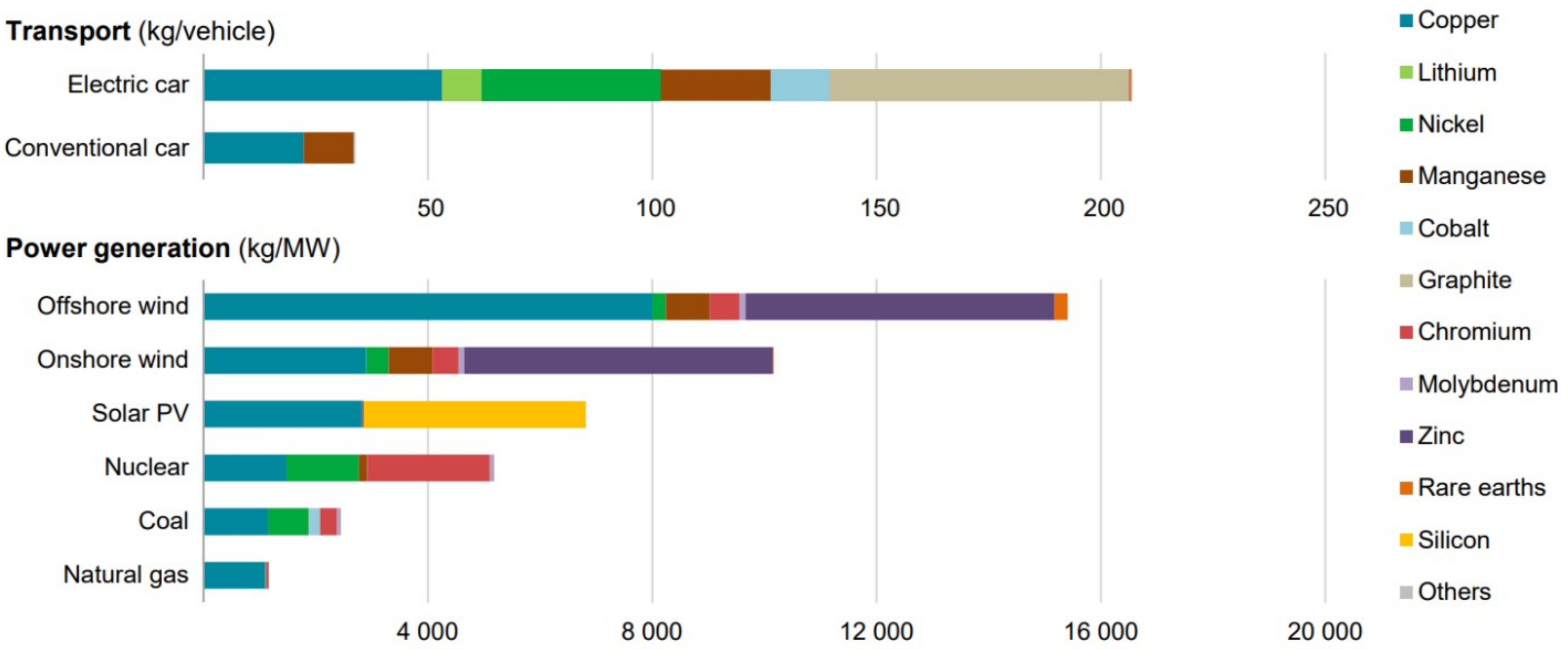
Example agrivoltaics. Source: climatebiz.com

curently Belgium is dependent of 80% for energy, with renewable we can reach 70%

not enough land, to much population density

Disadvantages of renewables (4): Critical materials

- The energy transition requires additional minerals
- There is a switch from fossil fuel extraction towards mining, although the involved quantities are much lower



Minerals used in selected clean energy technologies (Source: IEA, The Role of Critical Minerals in Clean Energy Transitions, 2021)

An example: the debate around rare earths

Novethic

"La transition énergétique est la plus fantastique opération de greenwashing de l'Histoire", selon Guillaume Pitron

"La transition énergétique est la plus fantastique opération de greenwashing de l'Histoire", selon Guillaume Pitron. C'est un livre choc sur la...

05 Mar 2018

Libération

Présidentielle Politique International CheckNews Culture Idées et Débats So

Accueil / International

Interview

Métaux rares : «Un véhicule électrique génère presque autant de carbone qu'un diesel»

Dans son dernier ouvrage, «La Guerre des métaux rares», Guillaume Pitron dénonce «la face cachée de la transition énergétique et numérique». Pour le journaliste, éoliennes, panneaux solaires et voitures électriques se contentent de déplacer la pollution à l'autre bout du monde.

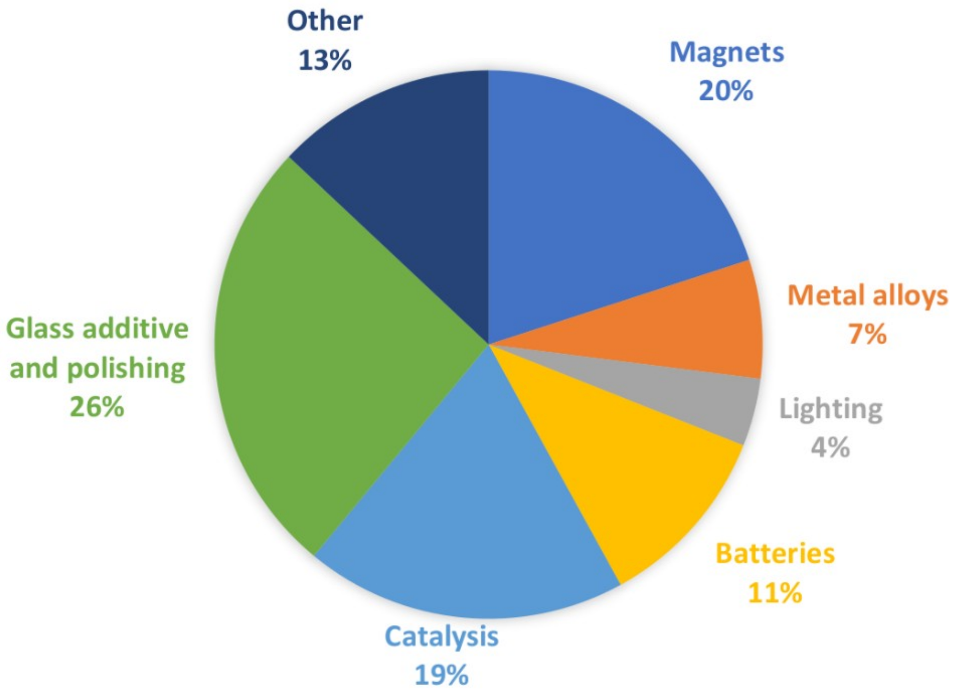
Révolution Énergétique

La transition énergétique va-t-elle manquer de matières ...

Par comparaison, la consommation de terres rares (qui, rappelons-le ne ... Guillaume Pitron, affirment l'impossibilité de la transition.

17 May 2021

Rare earths are not rare, they are already widely used

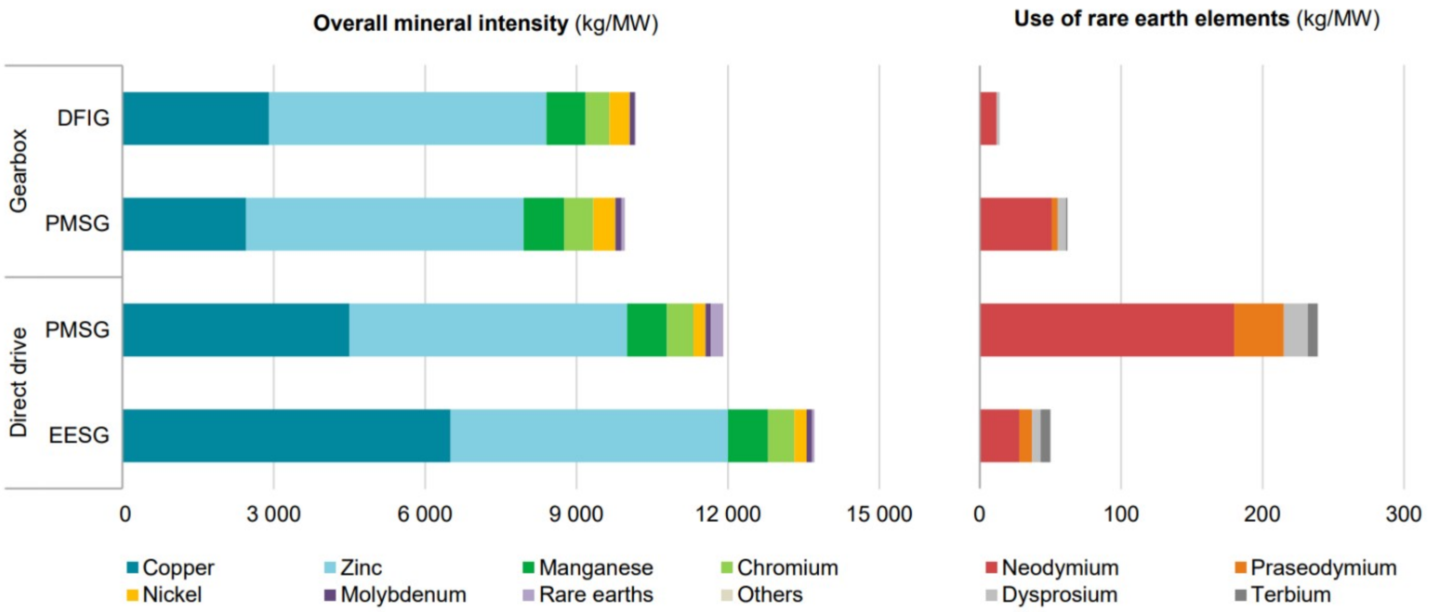


Source: https://lelementarium.fr/product/terres-rares/

- Rare earth elements are essentially used in two renewable energy technologies containing permanent magnet motors:
  - Wind turbines
  - Electric vehicles
- Demand side management (DSM) relies on the Internet or Things (IoT), which requires components such as indium
- There are no rare earths in Li-Ion batteries!
- The vast majority of PV modules do not contain rare earths

Rare earths can (sometimes) be substituded

- For wind turbines, rare earths intensive technologies can be substituted:
  - I DFIG (double-fed induction generators) account for more than 70% of the onshore wind market
  - I DD-PMSG (direct-drive permanentmagnet synchronous generator) account for 60% of the offshore market



Mineral intensity for wind power by turbine type (Source: IEA, The Role of Critical Minerals in Clean Energy Transitions, 2021)

Disadvantages of renewables (4): Critical materials

Rare-earth mining in China comes at a heavy cost for local villages

Pollution is poisoning the farms and villages of the region that processes the precious minerals

Health hazard ... pipes coming from a rare-earth smelting plant spew into a tailings dam on the outskirts of Baotou in China's Inner Mongolia autonomous region. Photograph: David Gray/Reuters

Source: http://theguardian.com

- The exploitation of rare earths in China has catastrophic environmental consequence
- China extracts 60% of rare earths in the world, but still has 90% of the refinery capacities
- However, a cleaner exploitation is possible, as indicated by Marx et al. (Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits, 2018)

Disadvantages of renewables (4): Critical materials

- Mineral resources are sufficient to enable the energy transition
- However, the environmental impact of their extraction and refinement cannot be neglected
- Many new technologies rely on rare earth materials. These 17 elements present similar physical properties are available in very low concentration in the earth crust. They generate high geopolitical and environmental issues for their extraction.
- Recycling of these materials is currently almost inexistent.
- Rare earths are not the only problem! Other (”critical”) materials must also be considered and might encounter some scarcities in the supply chain. For example:
  - Modern batteries technolgies require Lithium, with little substitution materials currently available.
  - Widespread electrification of the energy system will require metals such as copper, which also have environmental impacts
- **Substitution** is key! Alternatives to many critical materials exist, sometimes at the expense of a higher cost or lower efficiency. A cost-benefit and environmental impact analysis is required to compare all possible alternatives

Disadvantages of renewables (5): Impact on biodiversity

Example of offshore wind:
Potential impacts on biodiversity and the associated ecosystem services due to fixedbottom offshore wind developments

1. Bird and bat collision with, a) wind turbines and b) onshore transmission lines
2. Seabed habitat loss, degradation and transformation
3. Hydrodynamic change
4. Habitat creation
5. Trophic cascades
6. Barrier effects or displacement effects due to presence of wind farm
7. Bird mortality through electrocution on associated onshore distribution lines
8. Mortality, injury and behavioural effects associated with vessels
9. Mortality, injury and behavioural effects associated with underwater noise
10. Behavioural effects associated with electromagnetic fields of subsea cables
11. Pollution (e.g. dust, light, solid/liquid waste)
12. Indirect impacts offsite due to increased economic activity and displaced activities, such as fishing
13. Associated ecosystem service impacts
14. Introduction of invasive alien species

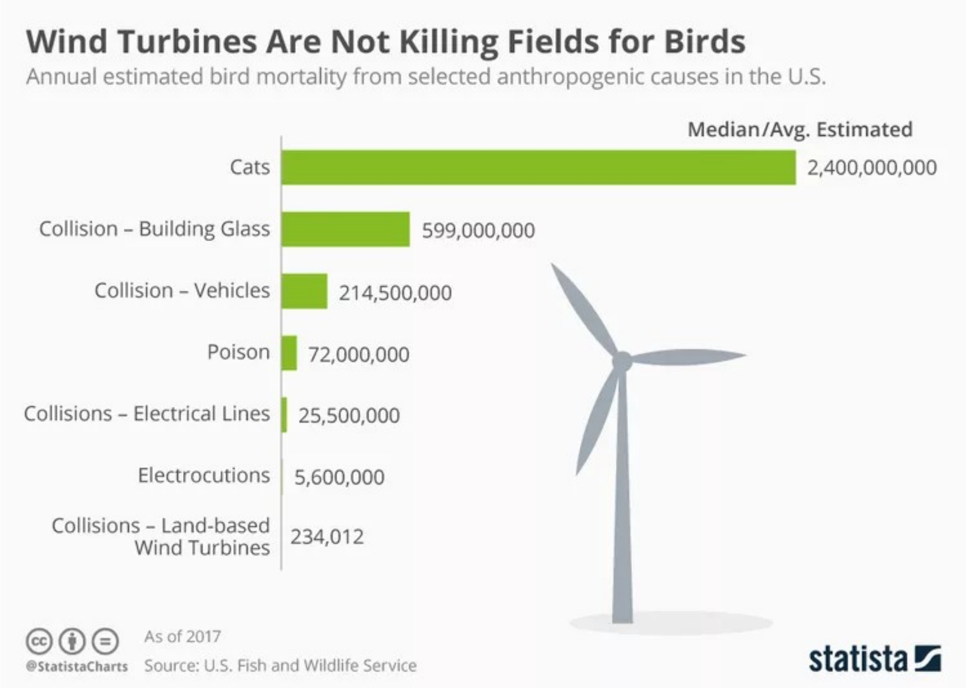
Positive impacts also exist!

- **The reef effect**. Submerged offshore structures attract a population of marine species that inhabit rocky environments enhancing biodiversity of the ecosystem
- **The reserve effect** on fish. The reduction or absence of fishing around offshore wind farms creates reservations for species.

Bennun, L., van Bochove, J., Ng, C., Fletcher, C., Wilson, D., Phair, N., Carbone, G. (2021). Mitigating biodiversity impacts associated with solar and wind energy development. Guidelines for project developers. Gland, Switzerland: IUCN and Cambridge, UK: The Biodiversity Consultancy.

Disadvantages of renewables (5): Impact on biodiversity

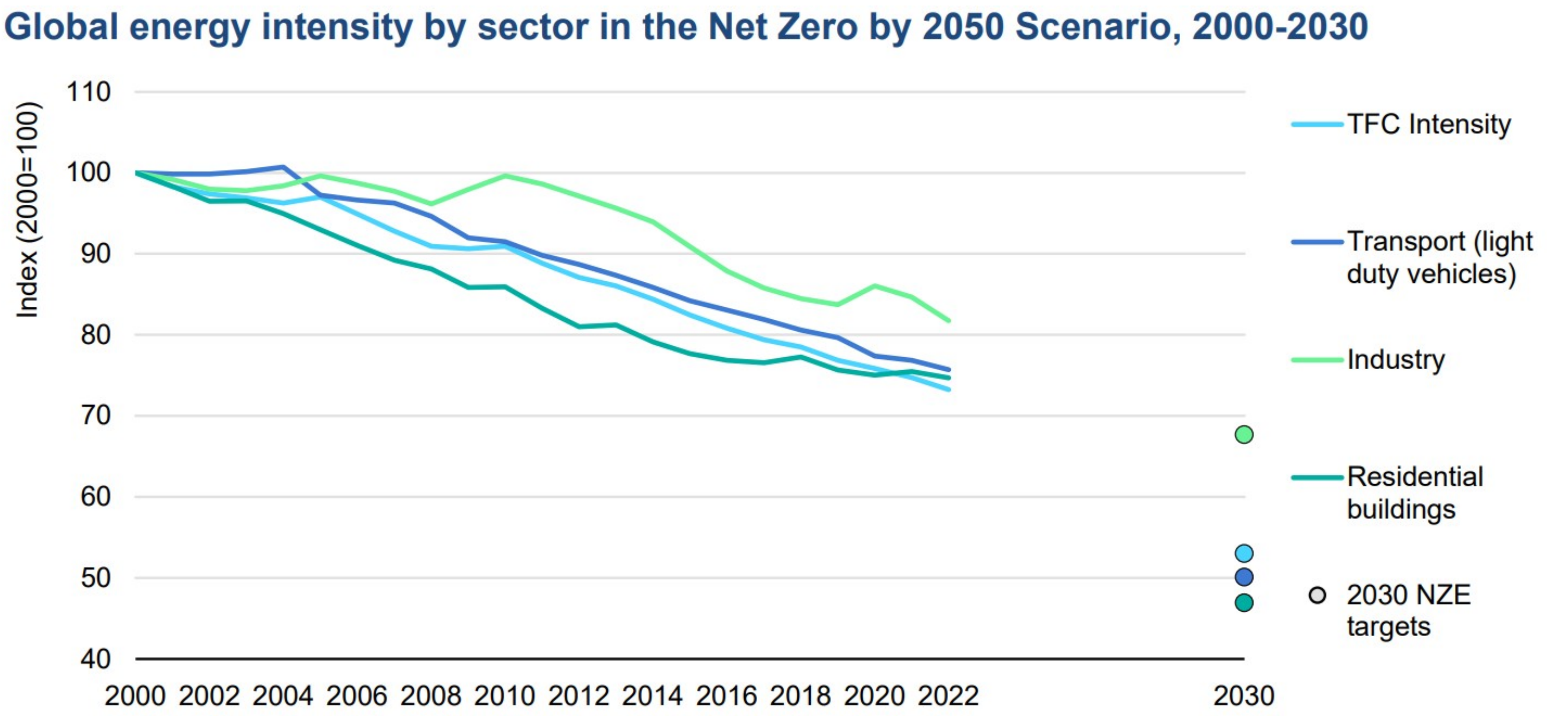
Impacts must be properly assessed and mitigating measures must be taken.
However, it is also important not to exagerate them.
An example:



Energy efficiency

Progress of energy efficiency in the world

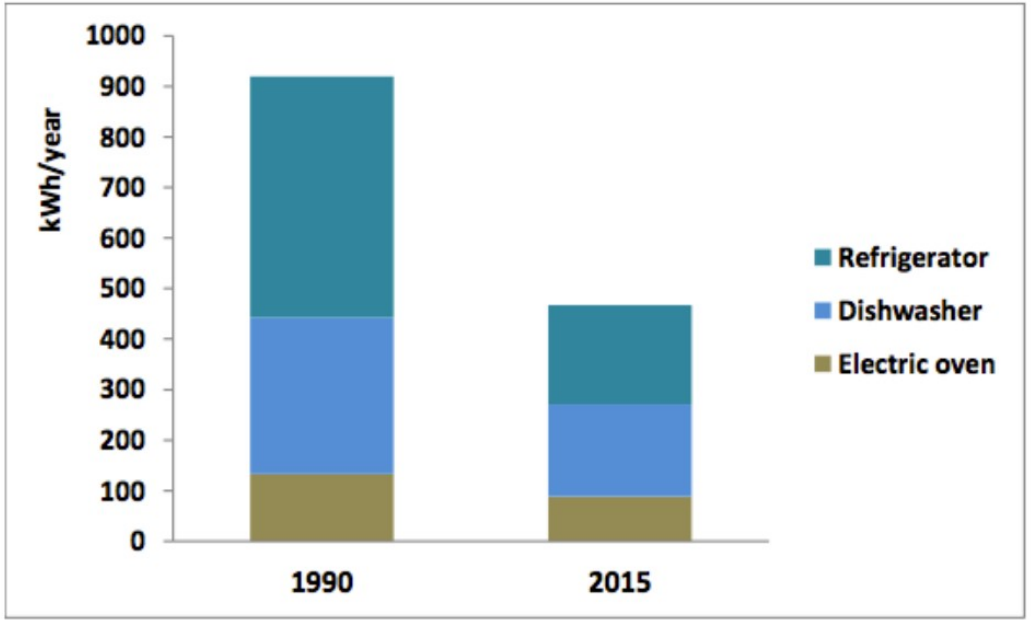
- Energy intensity is decreasing in all sector, but not fast enough to reach the net-zero emission target by 2050 (NZE scenario)

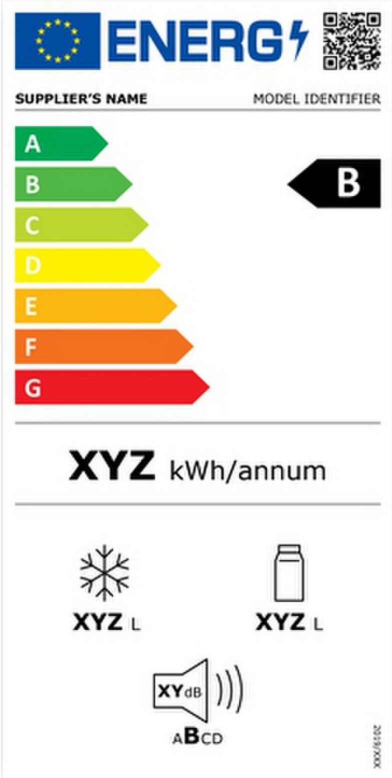


It's going in the good direction but not fast enough

Energy efficiency: some examples

Energy consumption of household appliances of the market average in 1990 and 2015 for three products :

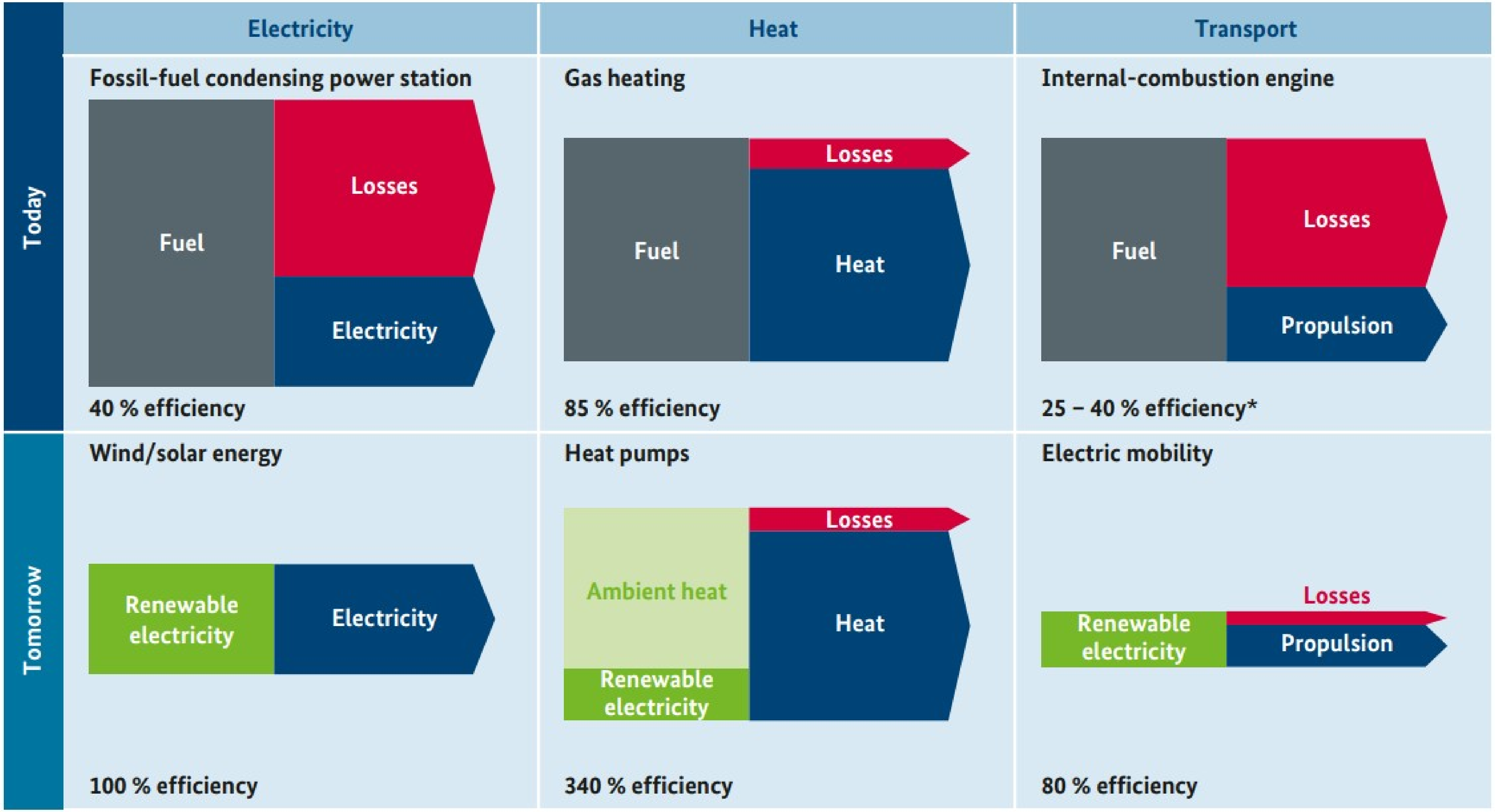




(source: VHK 2016, Toulouse/Attali 2018)

Efficiency of an current car ~15%

Energy efficiency: some examples



(source: BMWK, An electricity market for Germany's energy transition, 2015)

Energy efficiency: some examples

- Electrification of the heating sector presents an important potential for energy efficiency improvement

- In the example on the right, 26 GWh of electricity provide 70 GWh of heat, which would correspond to 78 GWh of fossil fuels with a traditional boiler (90% efficiency)

- The hydrogen pathway is clearly worse, because of the conversion losses to and from hydrogen

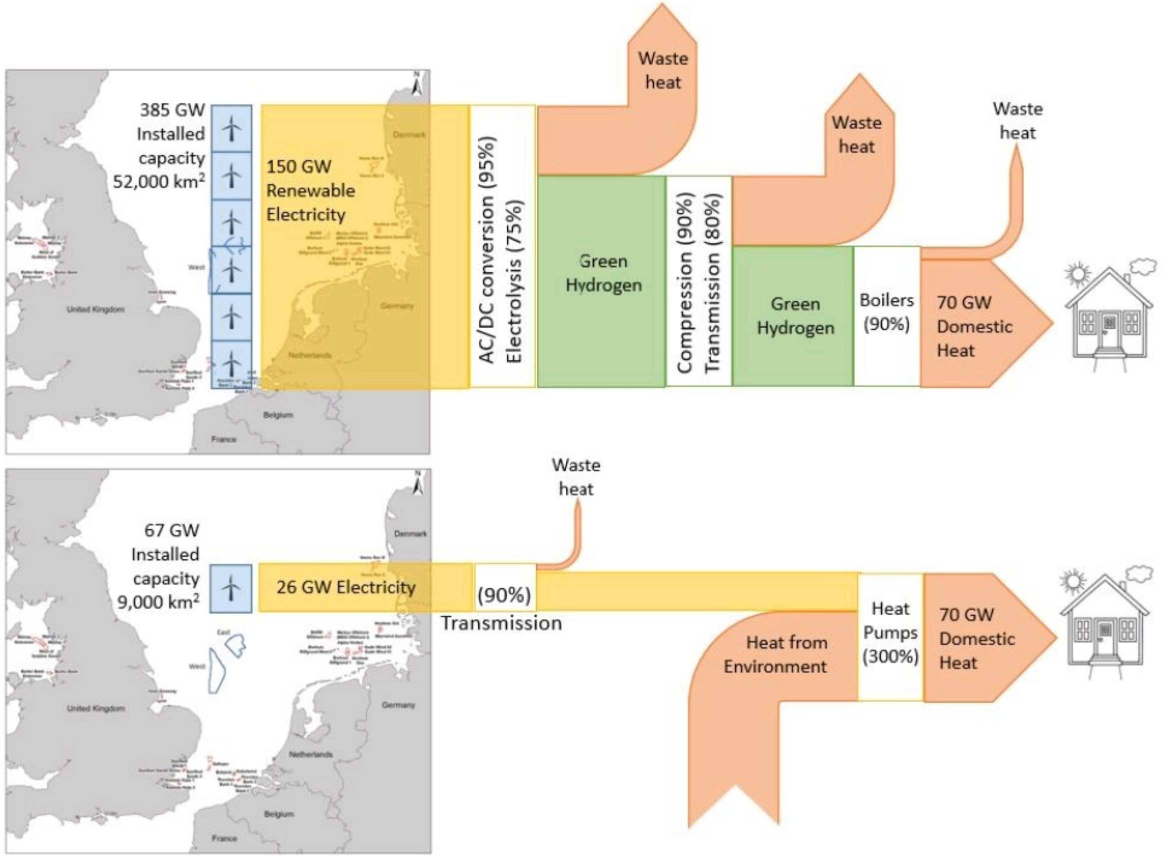
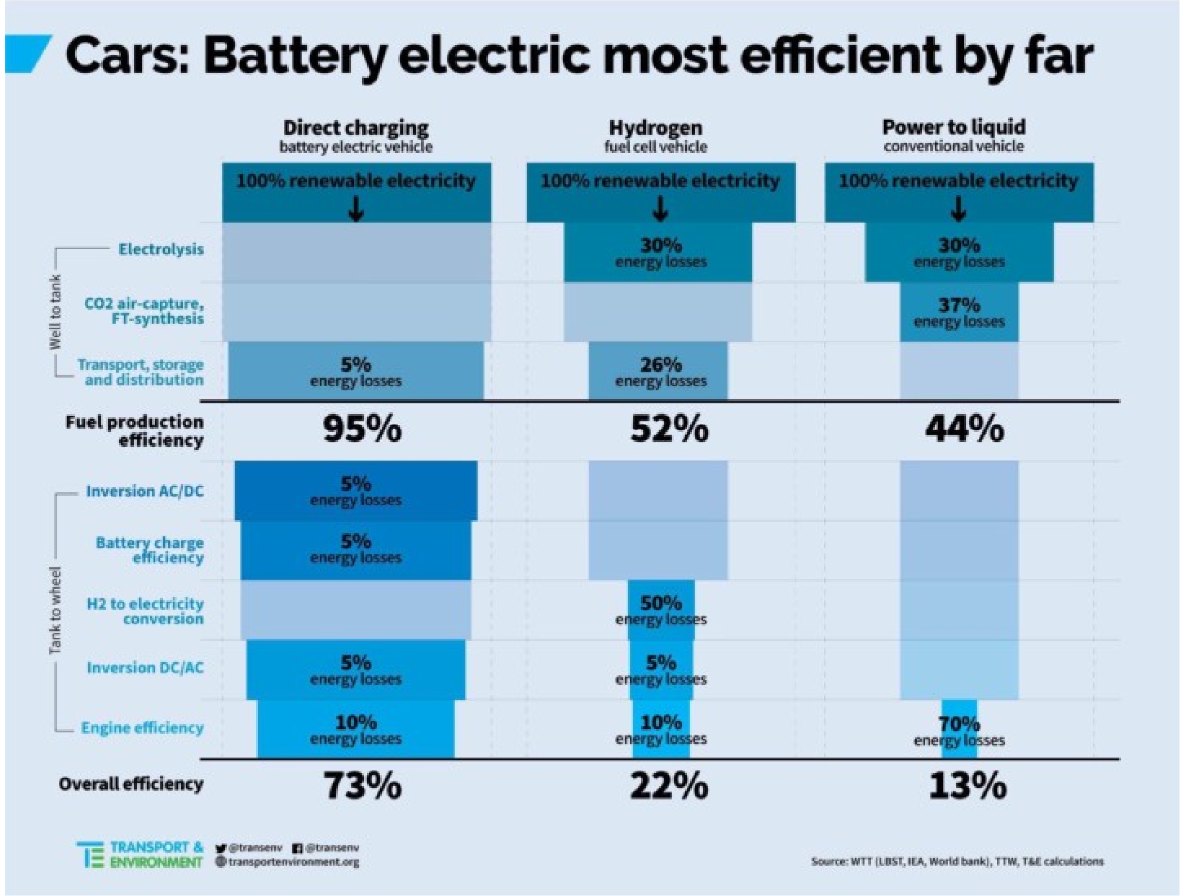


Fig. 1 Providing domestic heating in the UK using either Green Hydrogen or Heat Pumps. The colours of the arrows indicate the type of energy: electricity, green hydrogen or heat. The widths of the arrows are proportional to the power flows (in units of GW). The blue boxes show scaled areas of wind turbine farms on the maps. Red polygons on the maps are existing offshore wind turbine installations, which currently total approx. 10 GW.

Source: Hydrogen science coalition

Energy efficiency: some examples

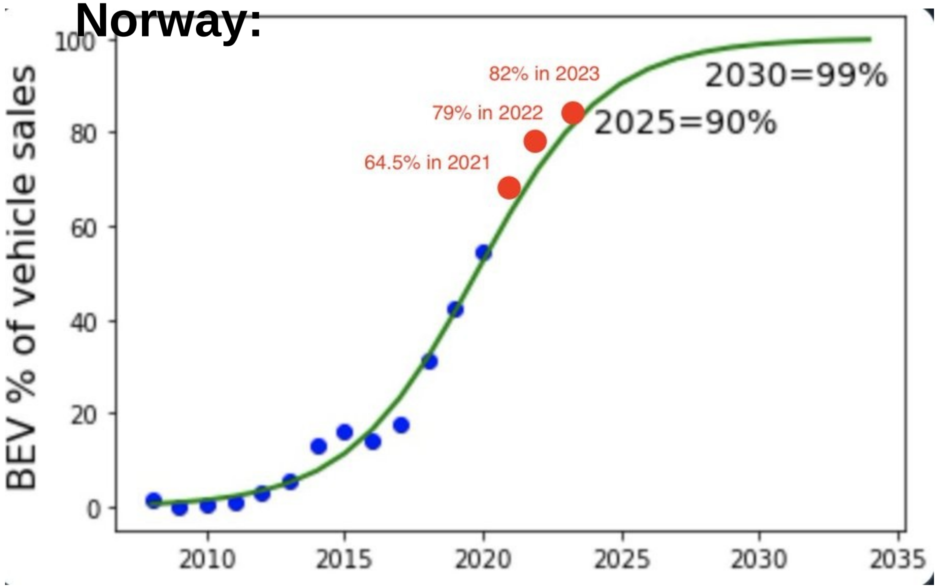
- Electrification of the transportation sectors also presents a significant energy efficiency potential.
- In the example on the right, the overall well-to-wheel efficiency of the electric vehicle is 73%
- The typical well-to-wheel efficiency of an internal combustion engine vehicle is lower than 30% (more than 70% energy losses).
- The hydrogen and power-to-liquid pathways are clearly less efficient

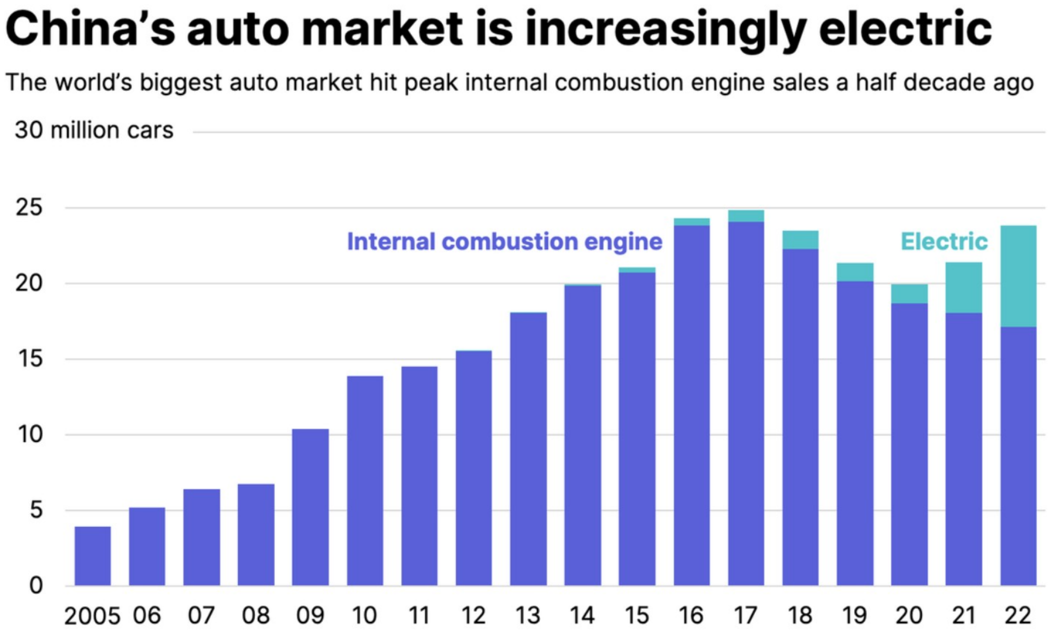


Energy efficiency: some examples

- Sales of battery-electric vehicles have reached 82% in Norway in 2023. China is following the same trend, but at an earlier stage.

Sales of BEV vehicles in Norway:





Sources: Emil Dimanchev (left), Nat Bullard (right)

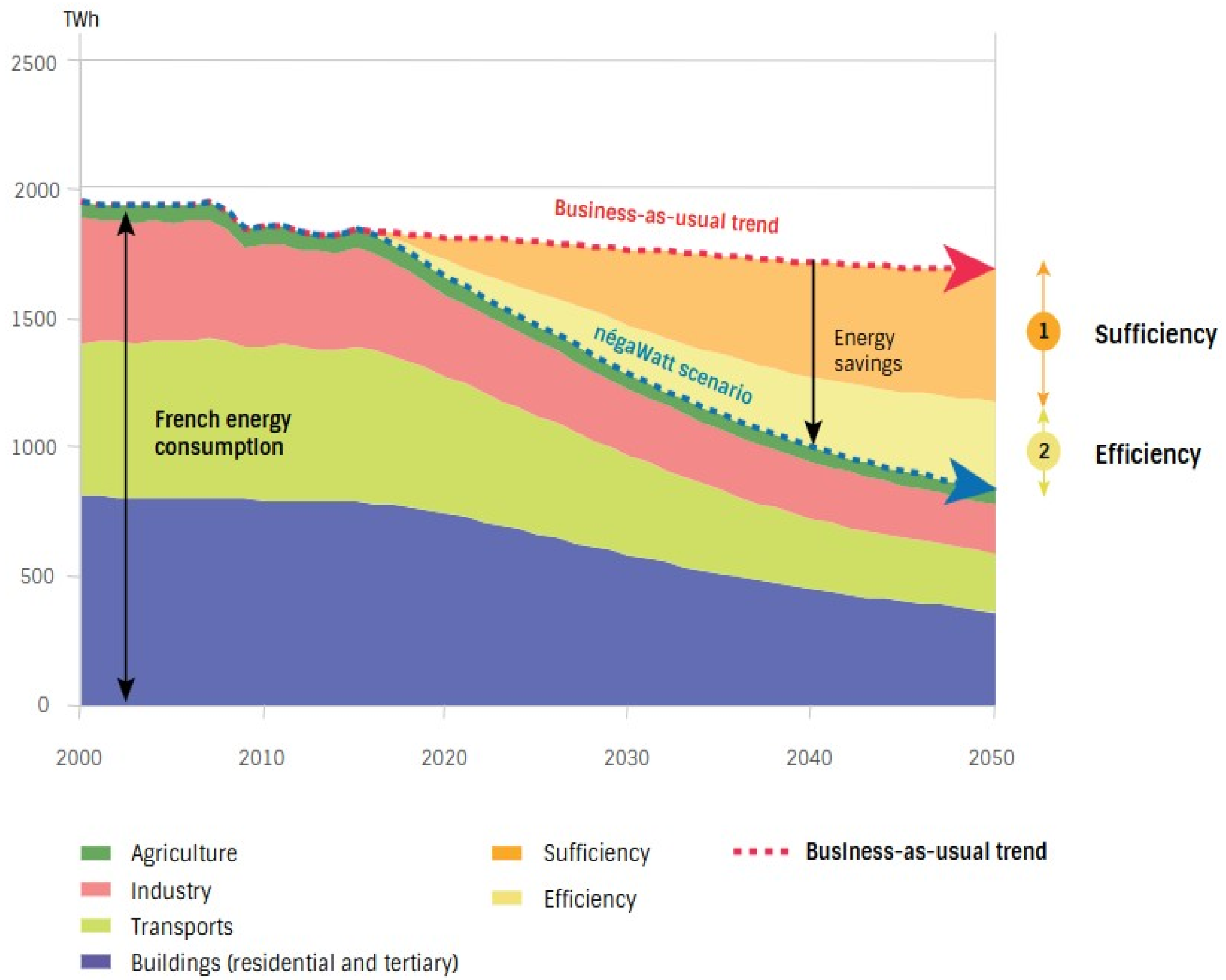
Energy sufficiency

IPCC AR6

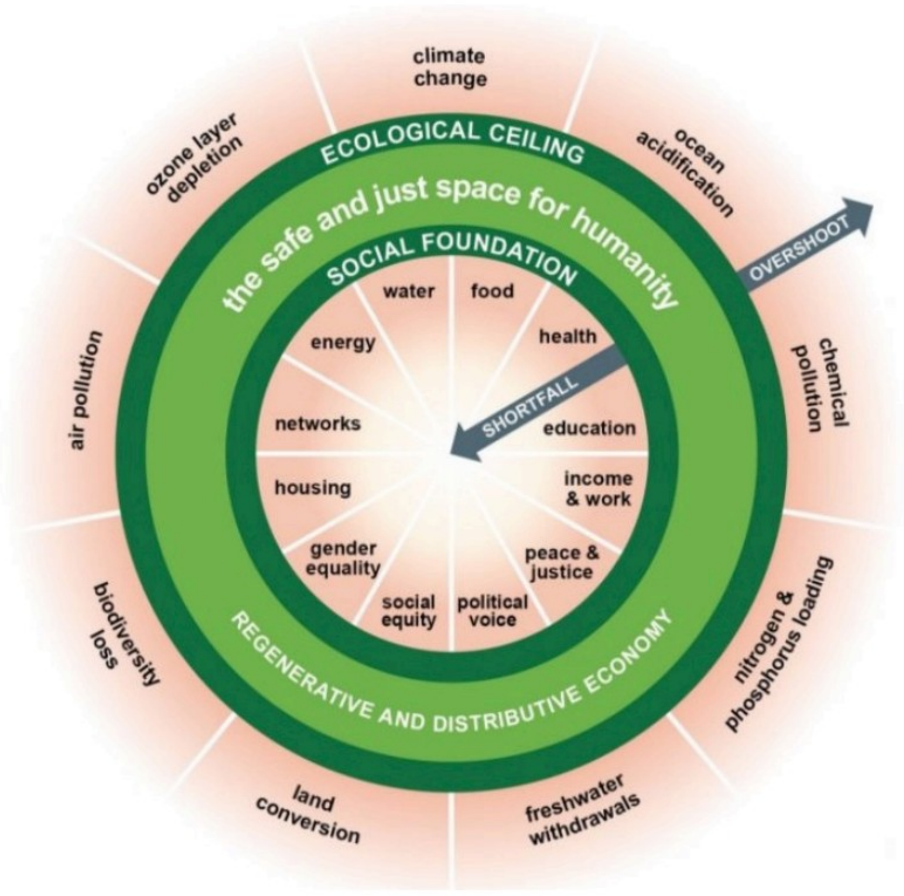
- IPCC definition of sufficiency:
  - *Sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries*
- New in the 6th report for WG3 (energy transition)
  - Much broader representation of social sciences: teams in almost all the chapters (not only climate scientists, economists or engineers)
  - More emphasis on justice and equity. “Just transition” is embedded in multiple chapters.
- Are we on track for 2°C or 1.5 ?
  - Consensus that we are behind on addressing climate change (high confidence)
  - Negative emissions:
    - Most scenarios of 2°C are valid only if we deploy negative carbon technologies globally
    - Technology is studied since more than 50 years, but has not be completely proven yet

Energy Sufficiency

- Transition towards climate neutral, sustainable and flexible economies
- Decreasing the overall demands by sufficiency measures (use of smaller cars, lower road speed, lower temperatures for space heating, car-sharing, home office slow tourism, etc.
- Individual and societal approach to decrease over consumption
- Respecting the planetary boundaries

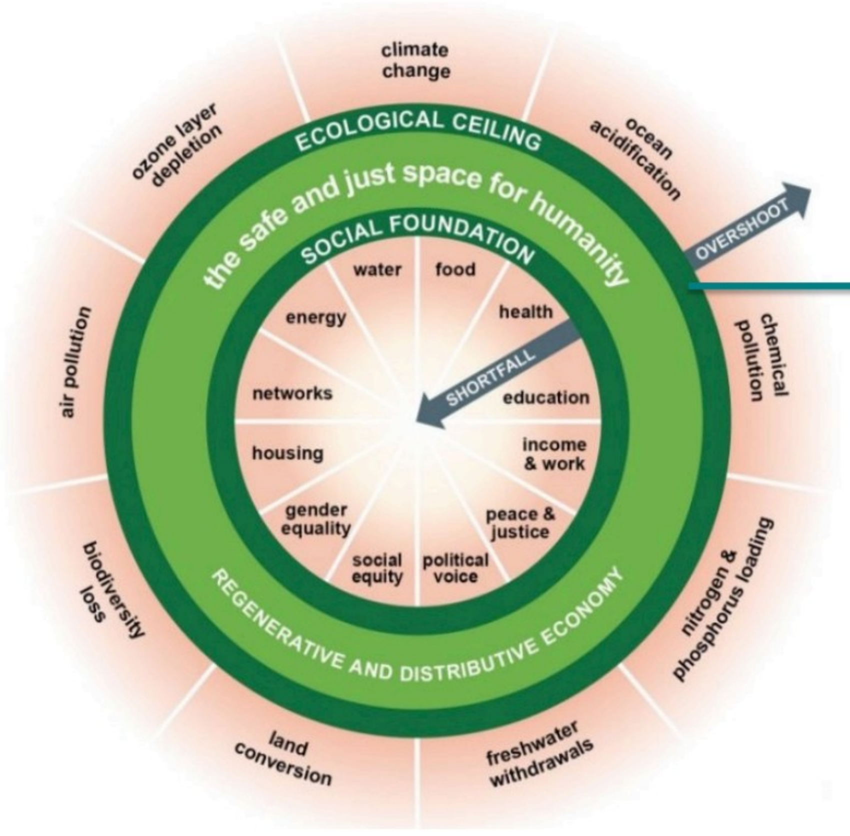


What is Sufficiency?

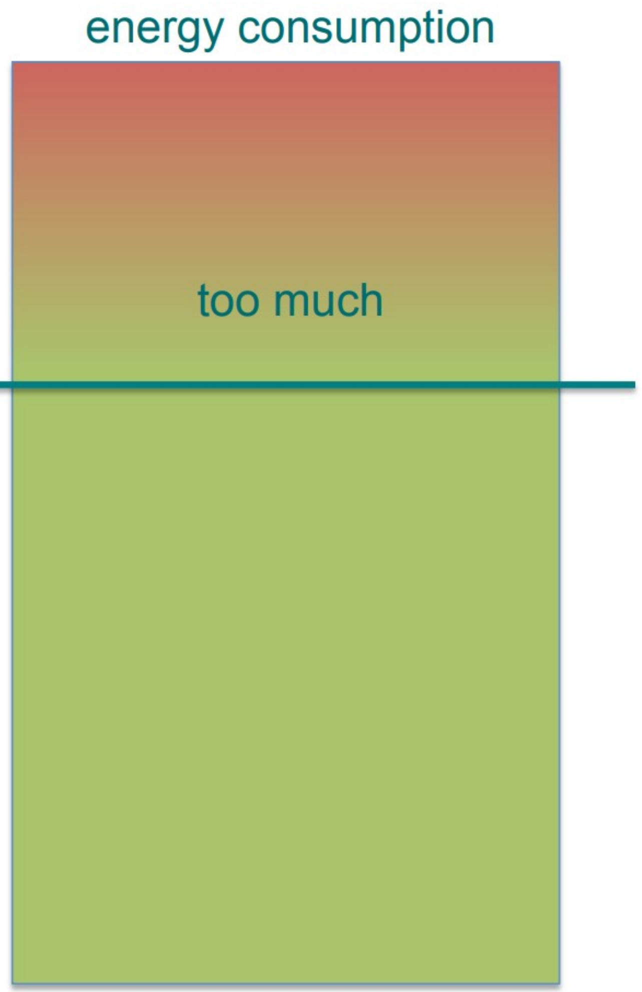


source: Kate Raworth "The Doughnut Economics"

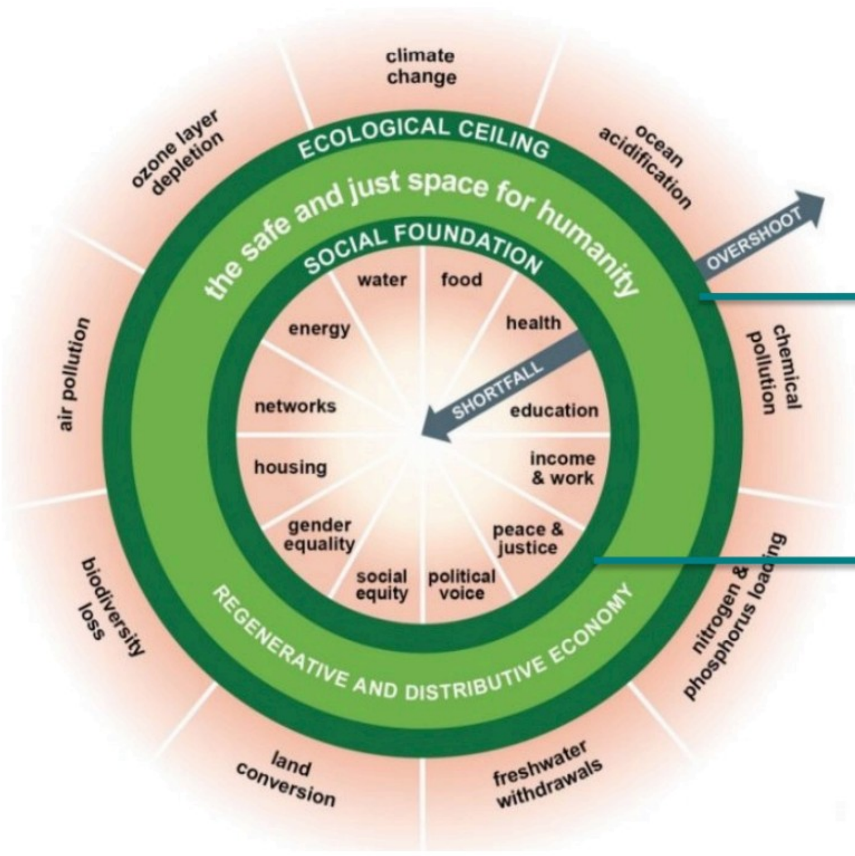
What is Sufficiency?



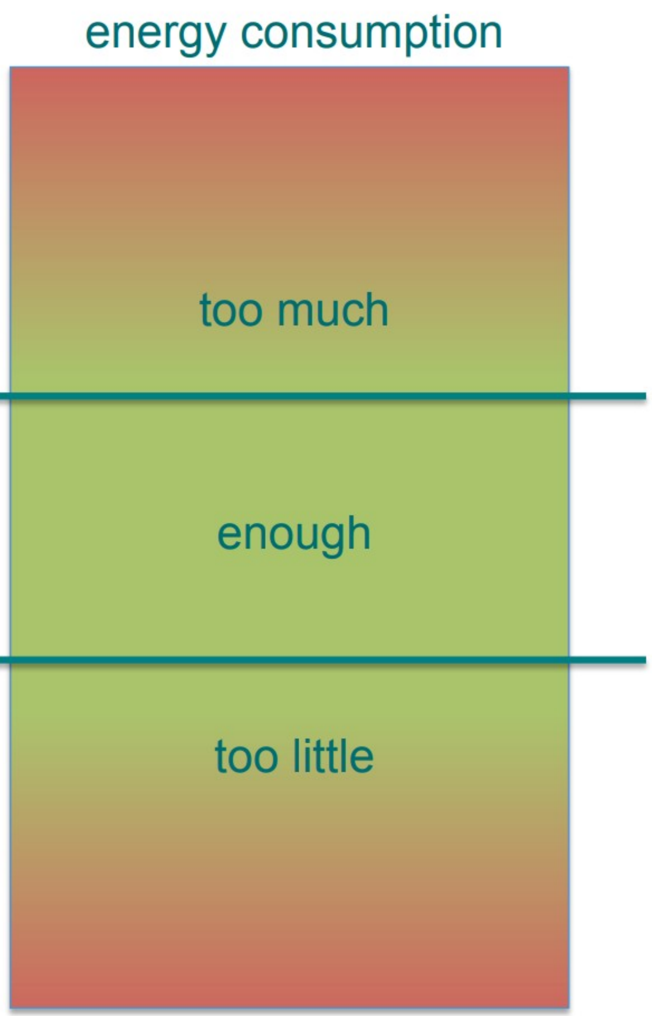
source: Kate Raworth "The Doughnut Economics"



What is Sufficiencv?

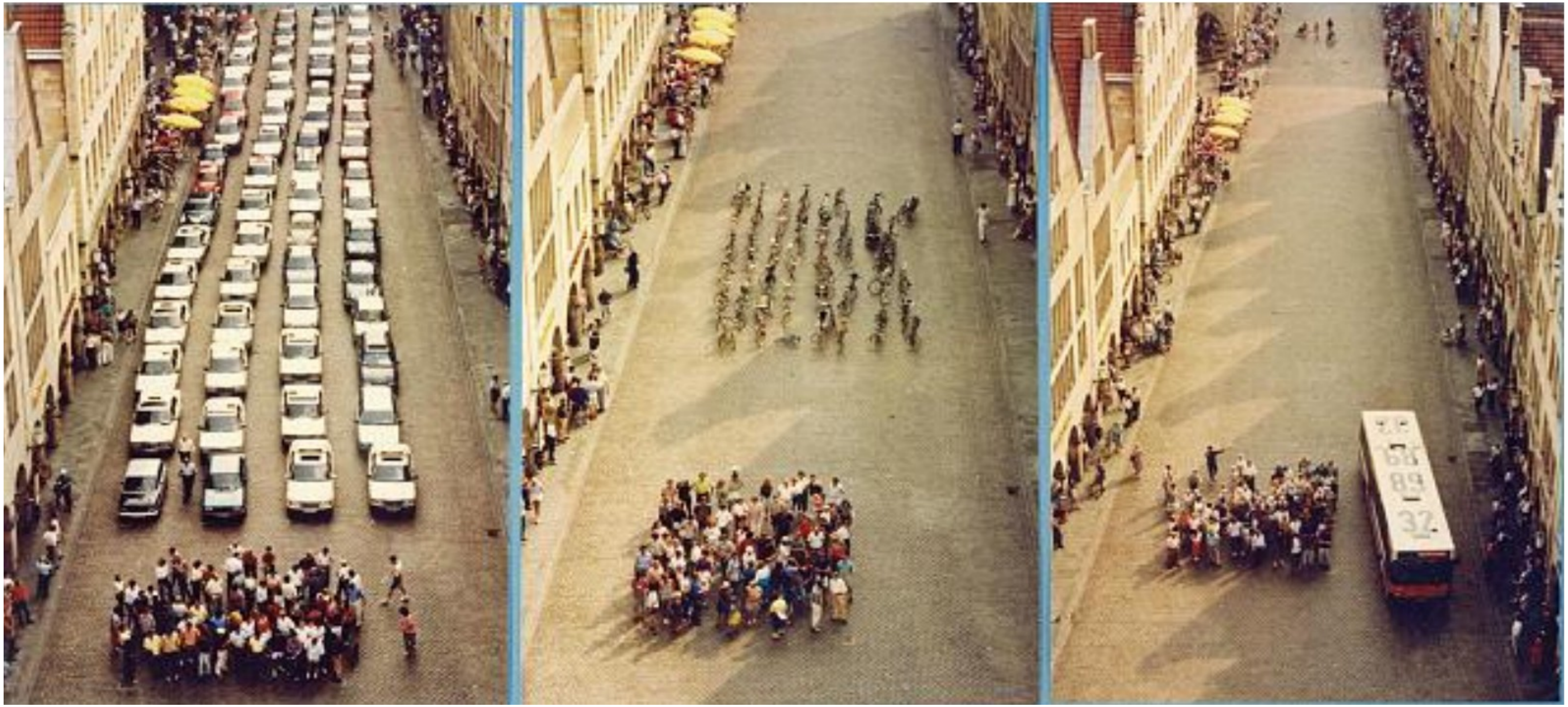


source: Kate Raworth "The Doughnut Economics"

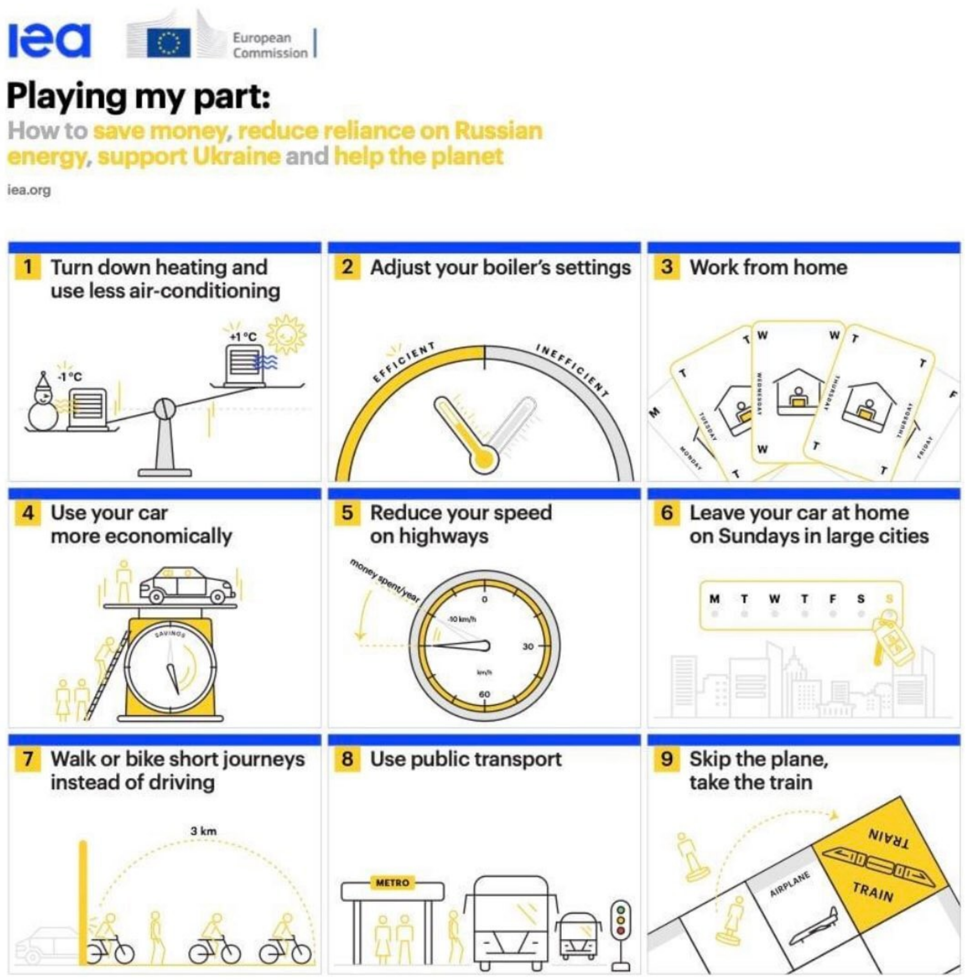


Energy sufficiency: some examples

Energy sufficiency: some examples



Energy sufficiency: some examples



Energy sufficiency: some counter-examples

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ACCUEIL • ÉCONOMIE • MOBILITÉ

Un salarié sur quatre a désormais une voiture de société

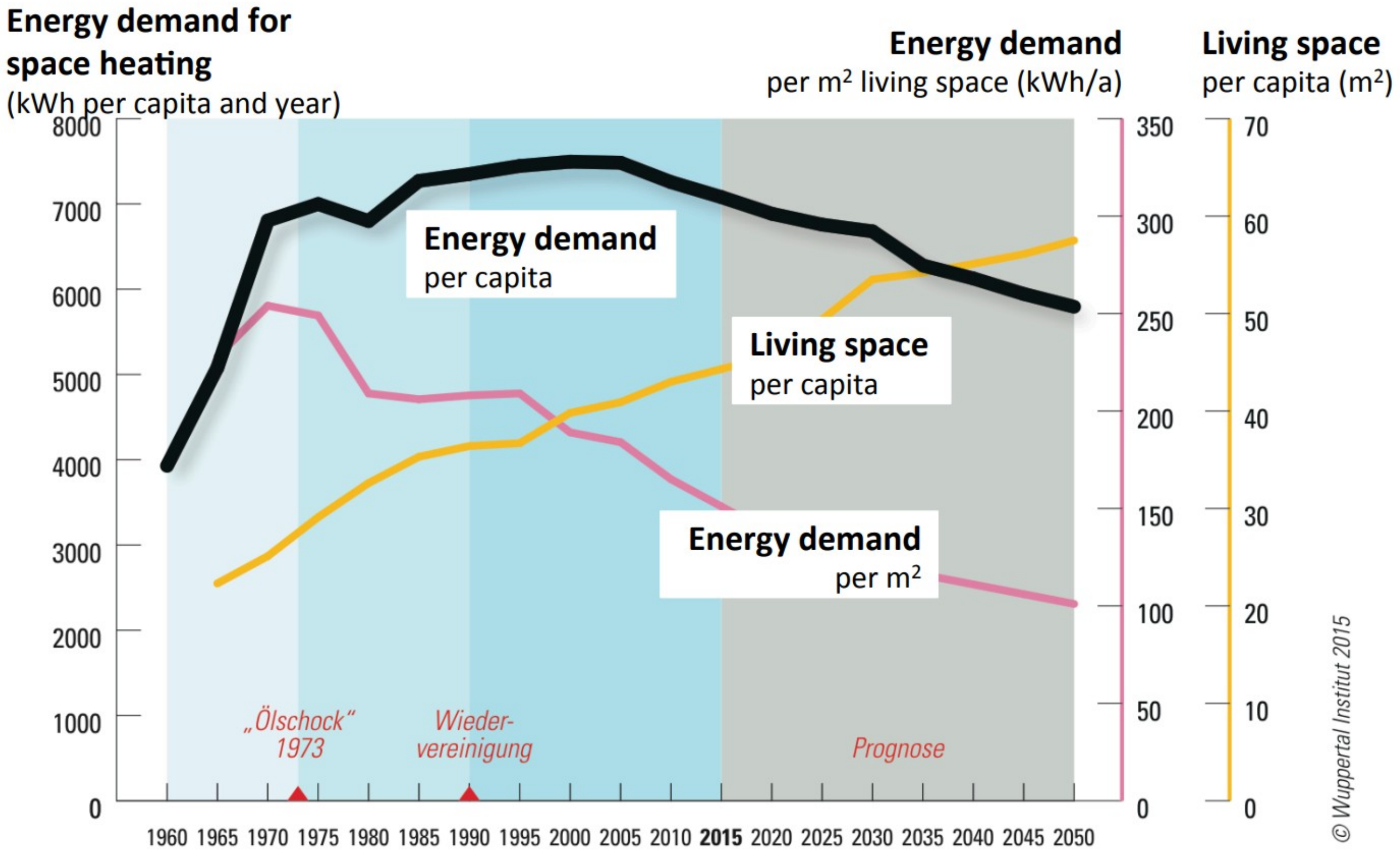
Malgré le télétravail, la part de salariés disposant d'une voiture de société augmente encore, atteignant 25 % selon Securex. Une décrue est observée à Bruxelles.

Article réservé aux abonnés

Energy sufficiency: some counter-examples

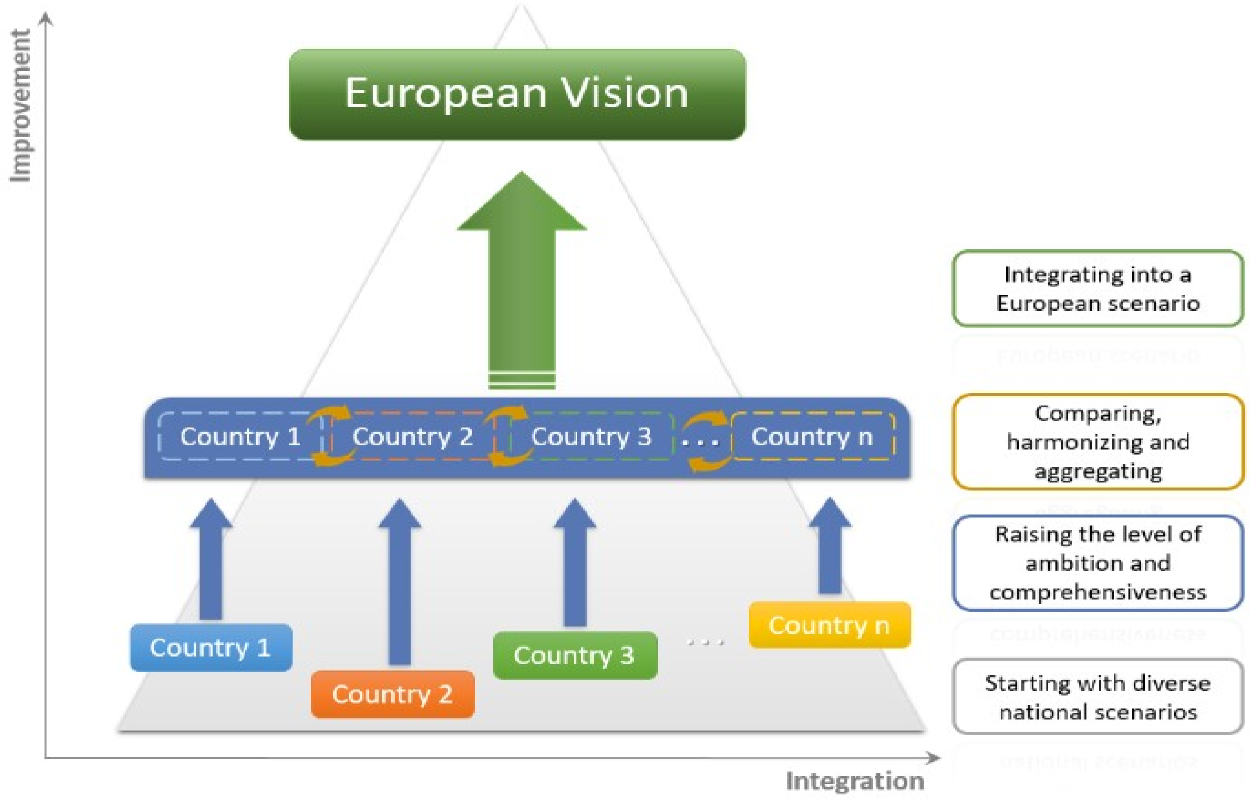
Energy sufficiency: some counter-examples

- A large part of the energy efficiency improvement in German buildings is canceled by the increase in the living space area



An example of energy sufficient sc CLEVER Scenario

- Bottom-up approach
- Carbon neutral by 2050 with 100% renewable technologies
- National sufficiency trajectories aggregated into a European pathway
- Quantifying the energy consumption at national level including the sufficiency assumptions
- Defining minimum consumption level on individual basis by prioritizing essential needs
- Carbon budget to reach 1.5C scenario



An example of energy sufficiency EU scenario: CLEVER

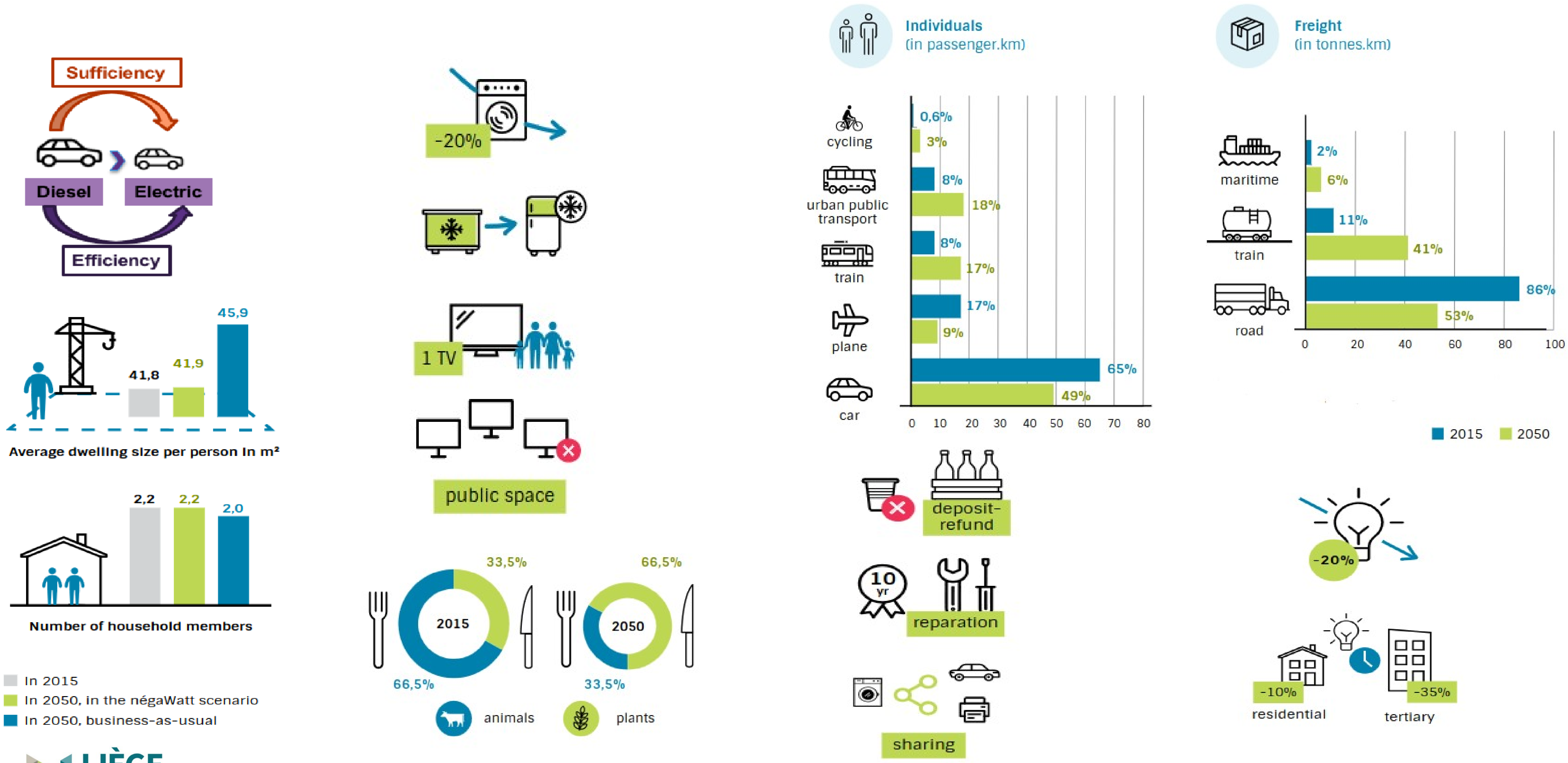
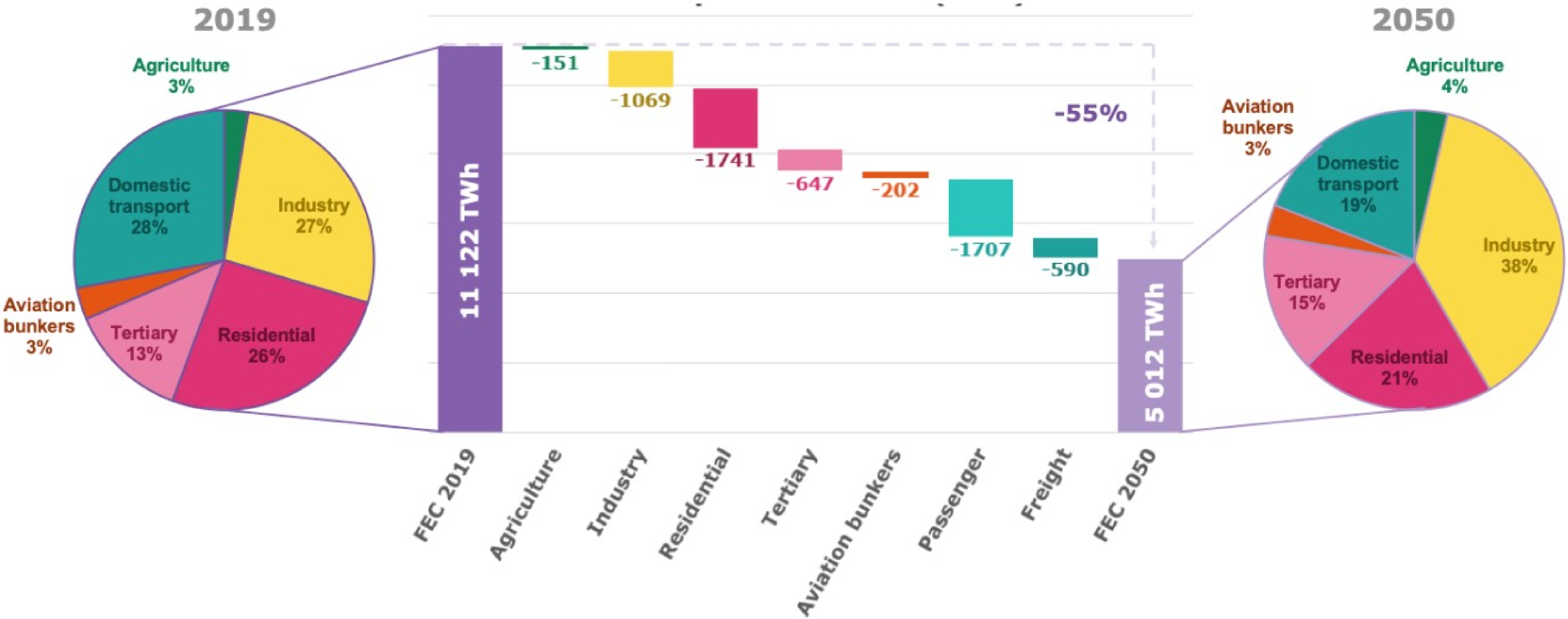


Image credentials: Clever – A Collaborative Low Energy Vision for the European Region – Final Report, June 2023

Demands in 2050



-55% reduction in final energy consumption
-20% to -30% thanks to energy sufficiency

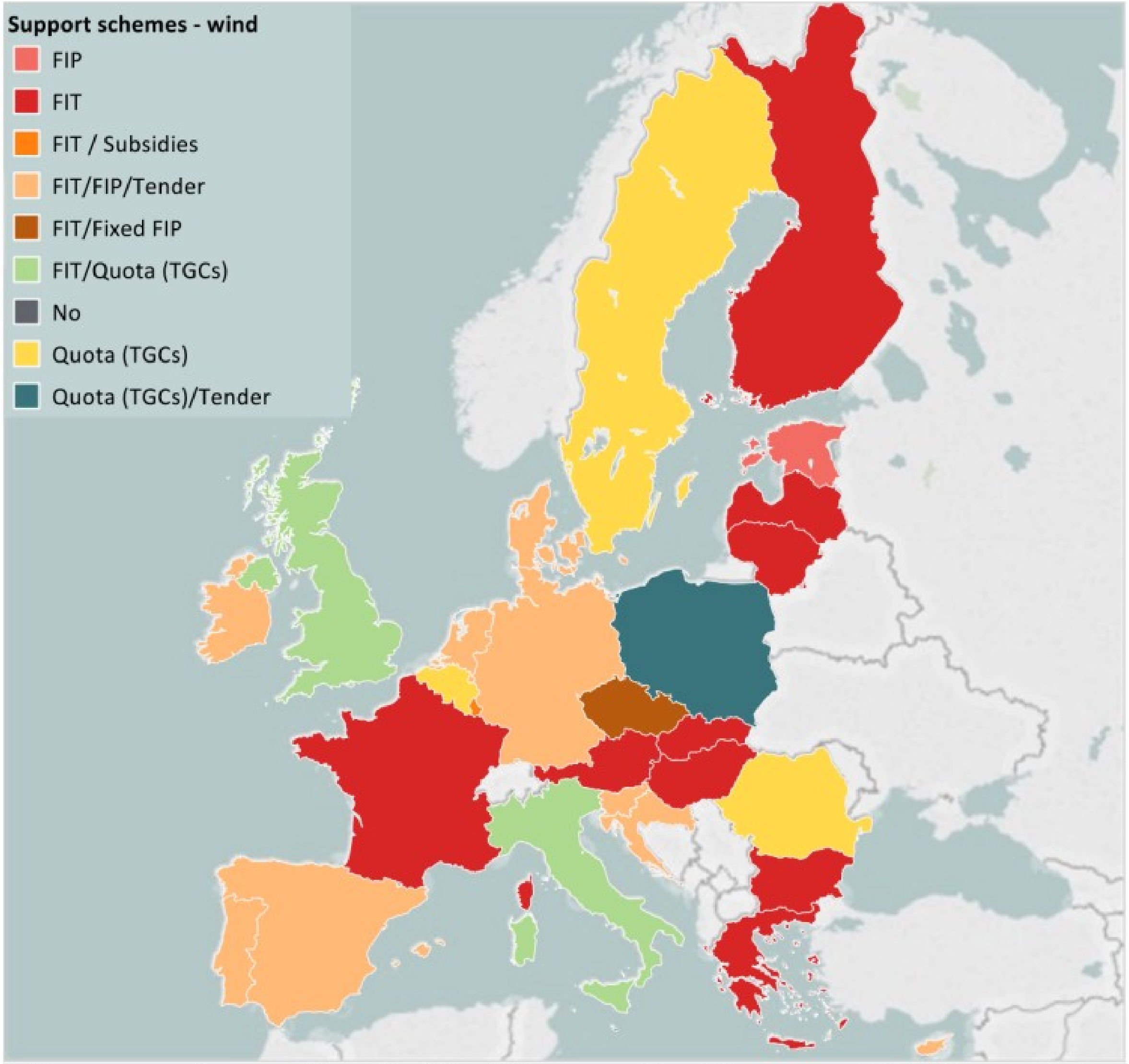
Image credentials: Clever – A Collaborative Low Energy Vision for the European Region – Final Report, June 2023

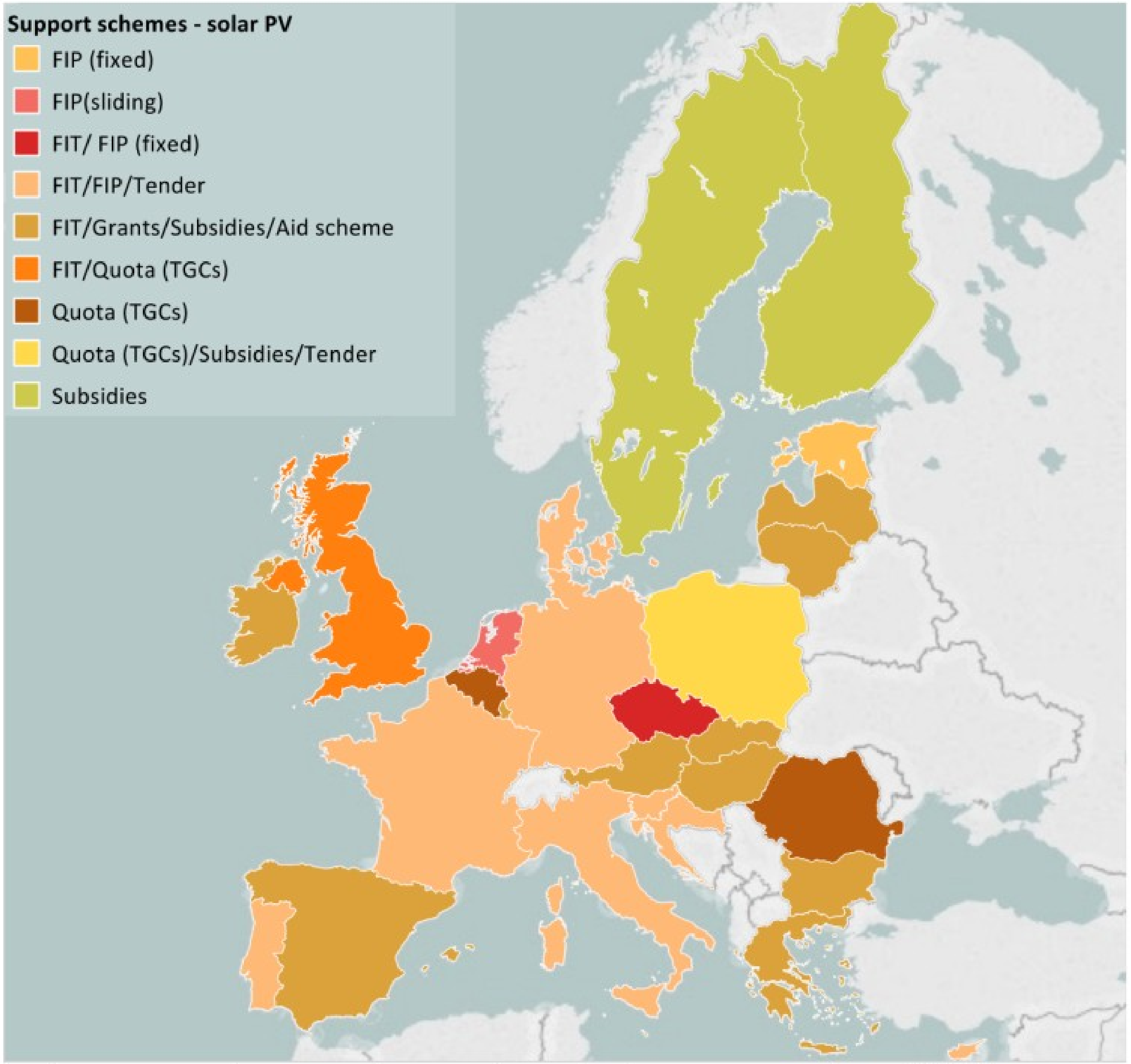
Energy policies to enable the transition

Support mechanisms

- Feed-in tariffs:
  - the energy from renewable sources is purchased by the system operator (or a supplier) at a fixed price (suppliers are obliged to take that output).
- Auctions:
  - a variation of feed-in-tariffs, in which an auction is organized by the government for a certain capacity of renewables. The winning companies are the ones bidding for the lowest tariff (i.e. accepting the lowest remuneration for their production)
- Quotas: in Europe is ETS
  - the suppliers are obliged to source a minimum fraction of their electricity from renewable sources.If the supplier cannot comply, obligations (penalities) can be bought for the shortfall. This system is often associated to Green Certificates. The quota can also be based on the emissions.
- Carbon Tax:
  - Fixed tax on the carbon emissions and, indirectly, favours the renewable sources.
- Tax Discount
  - Mostly on investment costs
- …

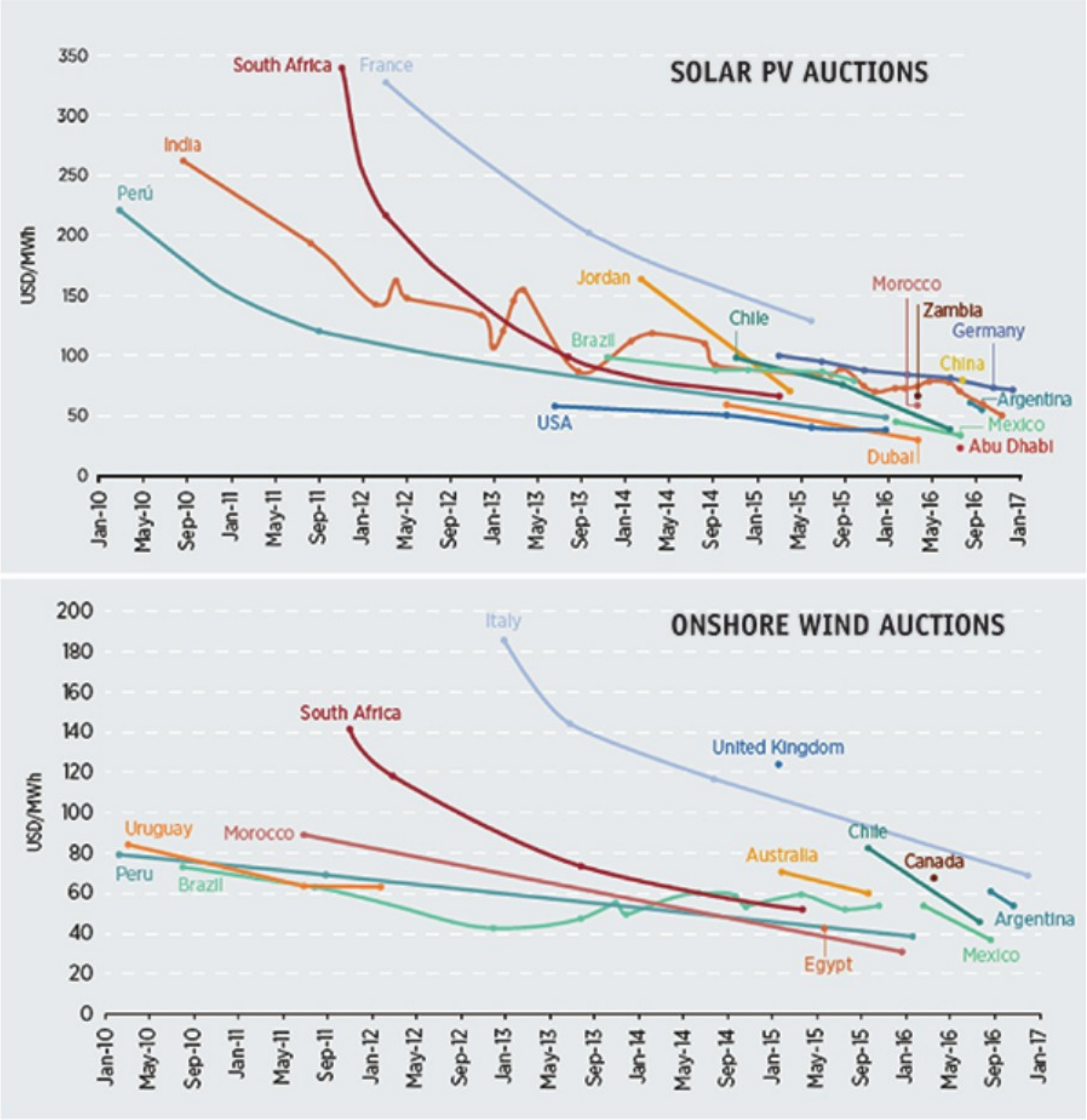
Different schemes in Europe





Support schemes for wind in EU countries (Source: JRC, Renewables in the EU: the support framework towards a single energy market, 2017)

Auctions



The real LCOE of electricity generation can be revealed through the results of ”Renewables Auctions”:

- Companies compete to build new renewable capacities with the lowest possible guaranteed tariff
- The price/kWh of the winning projects has been falling quickly in the last years

Climatehope @Climatehope2 · Dec 22, 2020

"Indian **PV auction** delivers final **record** low price of $0.0269/kWh." With solar prices this low, coal will wither away.

pv-magazine.com
Indian PV auction delivers final record low price of ...
The solar electricity price in India has dipped further to an all-time low of INR 1.99 ($0.0269)/kWh in a ...

1 · 3

Terje Osmundsen @OsmundsenTerje · Sep 11, 2018

Jordan Round 3 **PV auction** attracts **record** low bids pv-magazine.com/2018/09/10/jor...
What a revolution! In 2014 we signed one of the first contracts for solar in Jordan, with the FiT $0,16/kWh. Four years later: $0.02488/kWh!

7 · 4

Tim Buckley @TimBuckleyIEEFA · Feb 24, 2017

Indian electricity transformation: 1,000MW **wind auction** sets **record** low US5.2c/kWh Carmichael stranded @mattjcan 2/2

energy.economictimes.indiatimes.com
Wind power tariff falls to record low of Rs 3.46 a u...
Mytrah Energy (India) Private Ltd, Green Infra Wind Energy Ltd, Inox Wind Infrastructure Services Ltd ...

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BalkanGreEnNews @BalkanGreEnNews · May 31, 2020

At the country's 🇦🇱 second **#auction** for utility-scale #photovoltaics **#PV**, @VoltaliaSA offered to sell #electricity for just EUR 24.89 per MWh, a regional **record**.

balkangreenenergynews.com
Albania secures lowest solar power price in Balkan...
Albania said it would agree to the fixed price for half of the 140 MW solar power plant in Karavasta for 1...

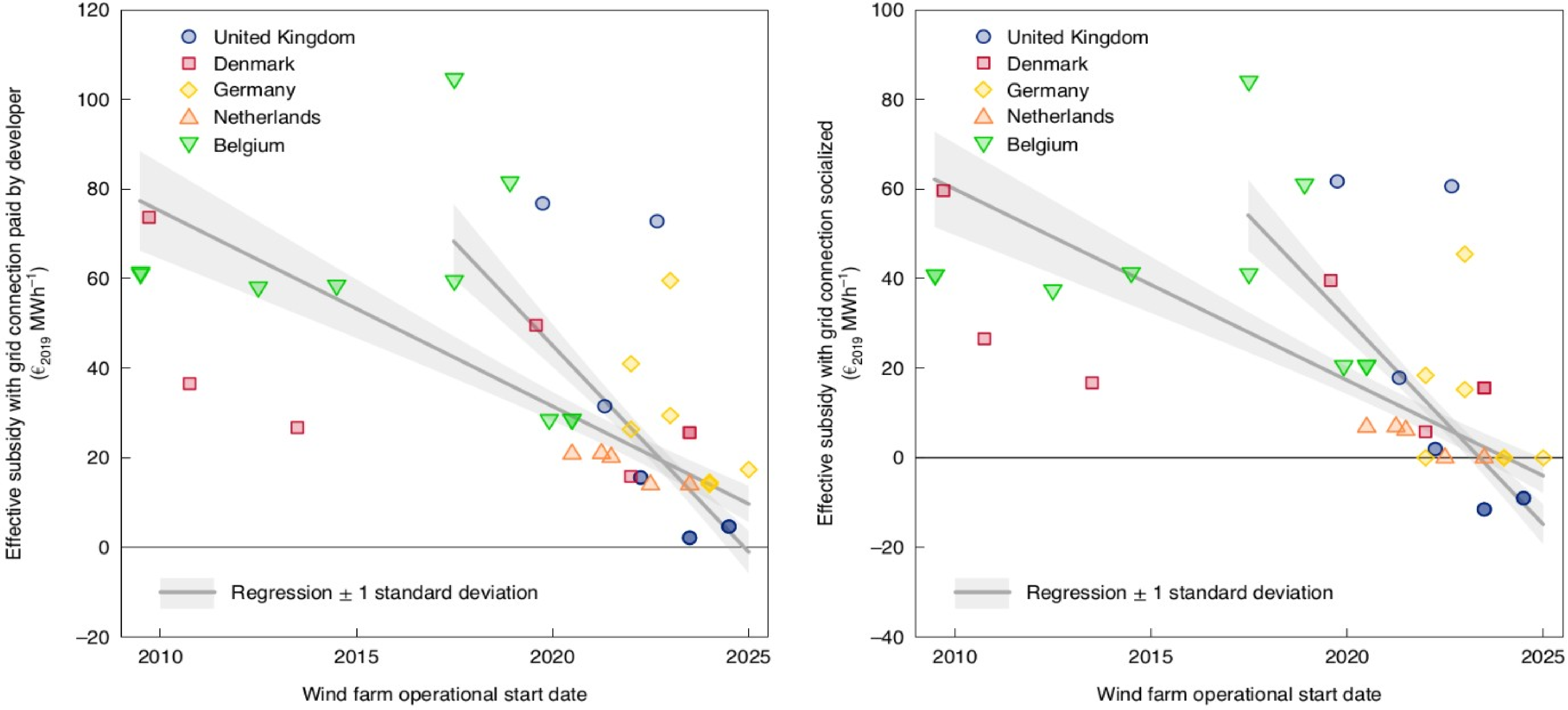
6 · 7

Alejandro Nuñez Jimenez @anunezjimenez · Jul 30, 2019

Portugal #solar **PV** prices shatter previous **record** with 14.76€/MWh contract (~16.44USD/MWh) to be built within 36 months in Southernmost part of country

With average price 20€/MWh, Portugal's **auction** demonstrates what spectacular developments await for South EU in coming years!

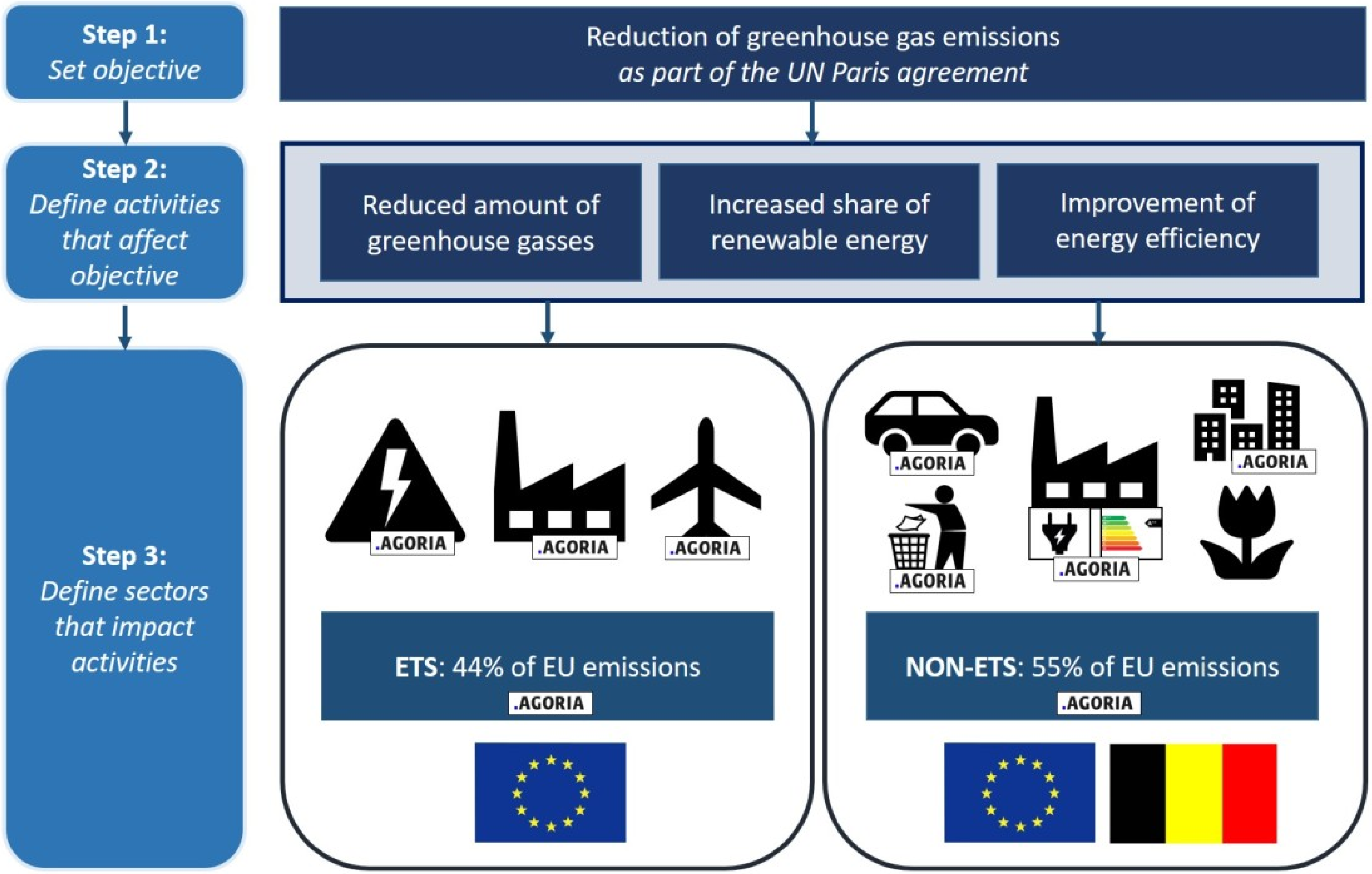
Example: auctions for offshore wind



Effective subsidy for each offshore wind farm auctioned in Europe. Source: Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. Nature Energy

LIÈGE université

The European Emission Trading System (ETS)



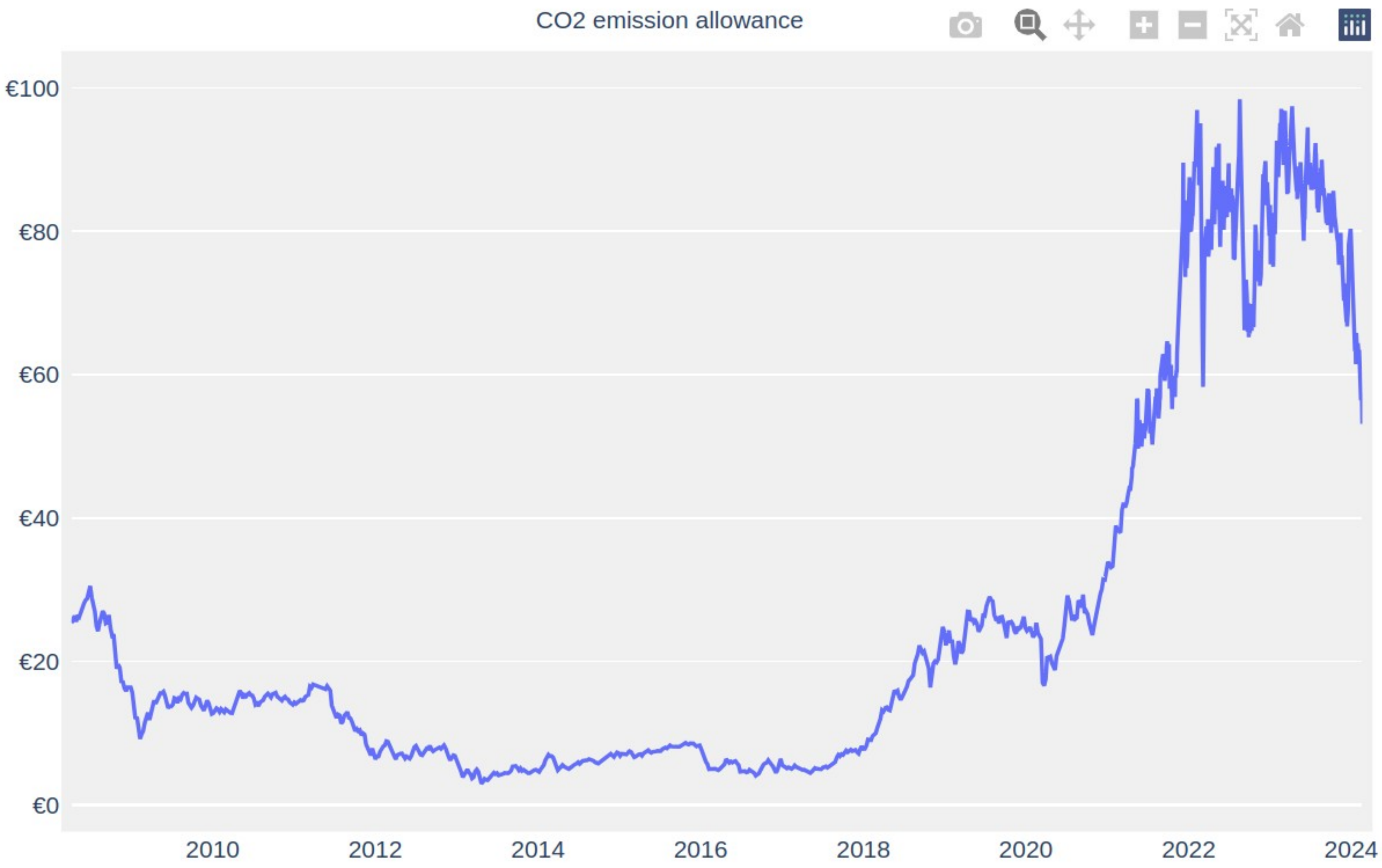
Schematic representation of the design of the European climate legislation (Source: C.J. van der Veer - Agoria)

ETS description

The ETS is a quotas (or cap and trade) system on CO_2 emissions set up in the European Union. It limits the total amount of CO_2 that can be emitted, and creates a market where emission allowances can be traded.

- Because of an oversupply of ETS (due to various reasons such as an excess free allowances allocated to some industries, to the economic downturn, etc), the price for one ton of CO_2 has remained very low (a few euros) $\Rightarrow$ the influence of ETS on energy markets is negligible.
- However, since 2017-2018, prices have gone up, which is due to diverse reasons such as the reduction of the oversupply (back-loading) or the economic recovery.
- To prevent **carbon leakage**, i.e. the risk of relocating the production of certain sectors outside of the EU, free allowances are given to industrial installations belonging to a sector deemed at risk of carbon leakage. This system is expected to last at least until 2030
- In the fourth phase (2021-2030), number of emission allowances declines at an annual rate of 2.2% (compared to 1.74% previously). The goal was -43% by 2030 compared to 2005, and was upgraded to reach an overall -55% for all sectors by 2030.

ETS price evolution



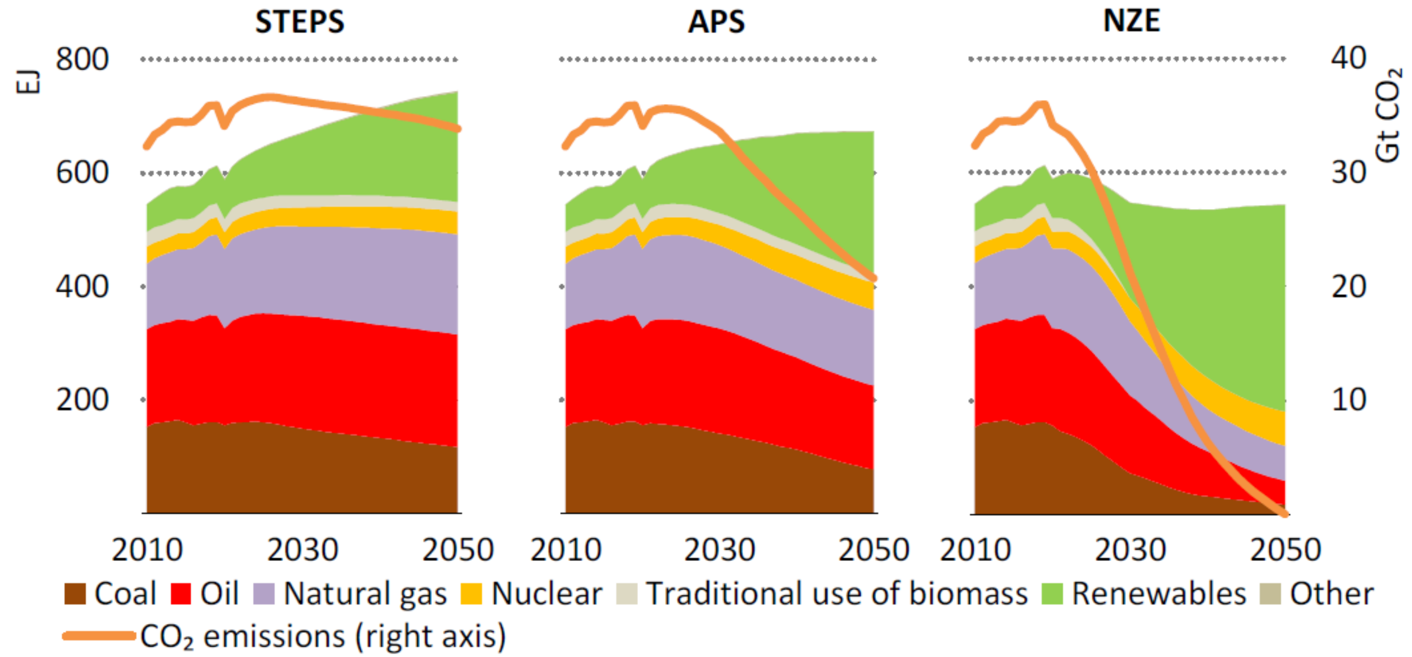
Source: Source:sandbag.be

Modeling energy policies? The IEA example

- The IEA World energy outlook defines three scenarios:
  - STEPS: Stated Policies Scenario
  - APS: Announced Pledges Scenario
  - NZE: Net zero Emissions scenario

It appears clearly that the announced pledges are insufficient to meet the goals of the Paris agreement (commitment gap), and that the stated policies in each countries are far from sufficient (Emission gap)

Figure 4.1 ▷ Total primary energy supply by fuel and scenario



Source: IEA World Energy Outlook 2021

Conclusions