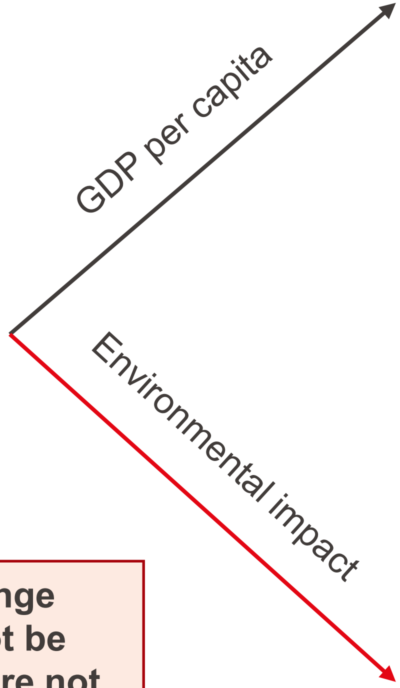
Energy supply, economics and transition

Decoupling

Professor Philippe Thalmann



Slides with an orange background will not be shown in class and are not exam material; read them if you are interested

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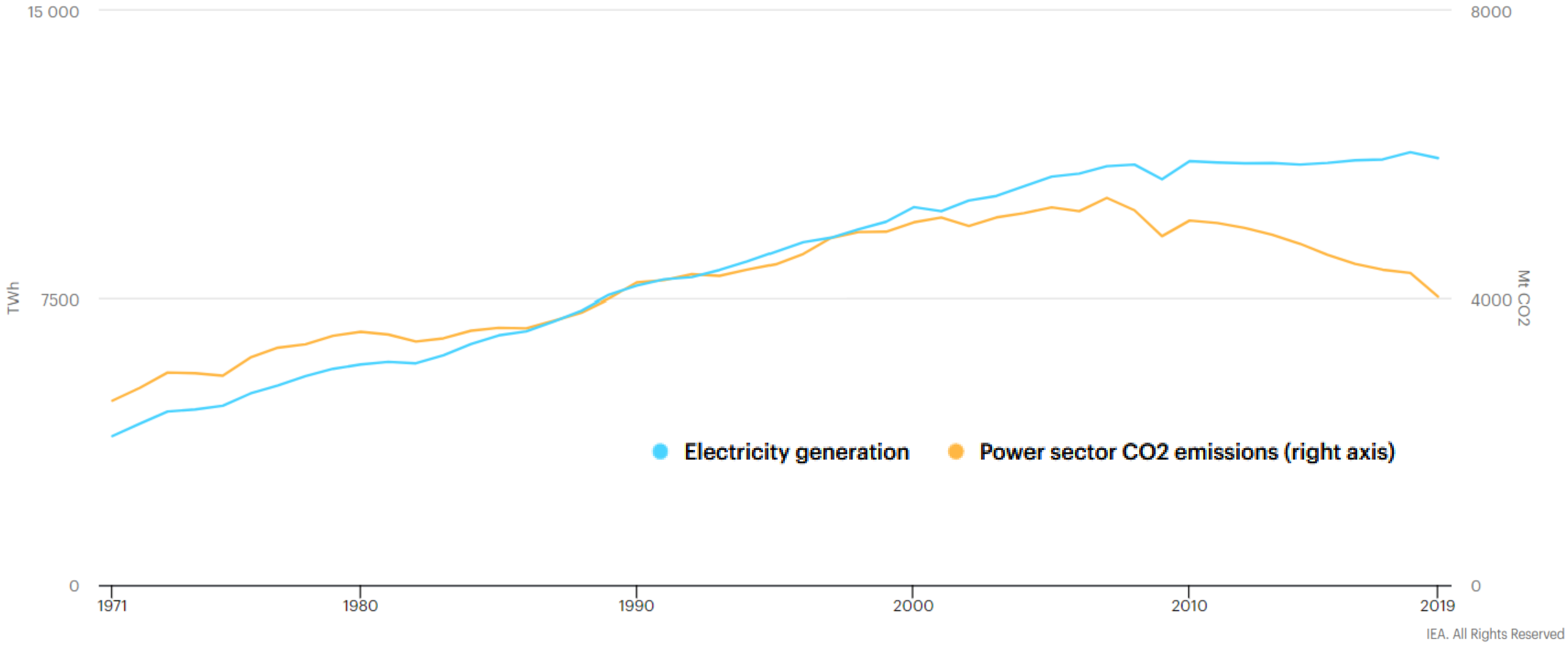
Decoupling defined

Decoupling of power sector CO_2 emissions from electricity generation in advanced economies*



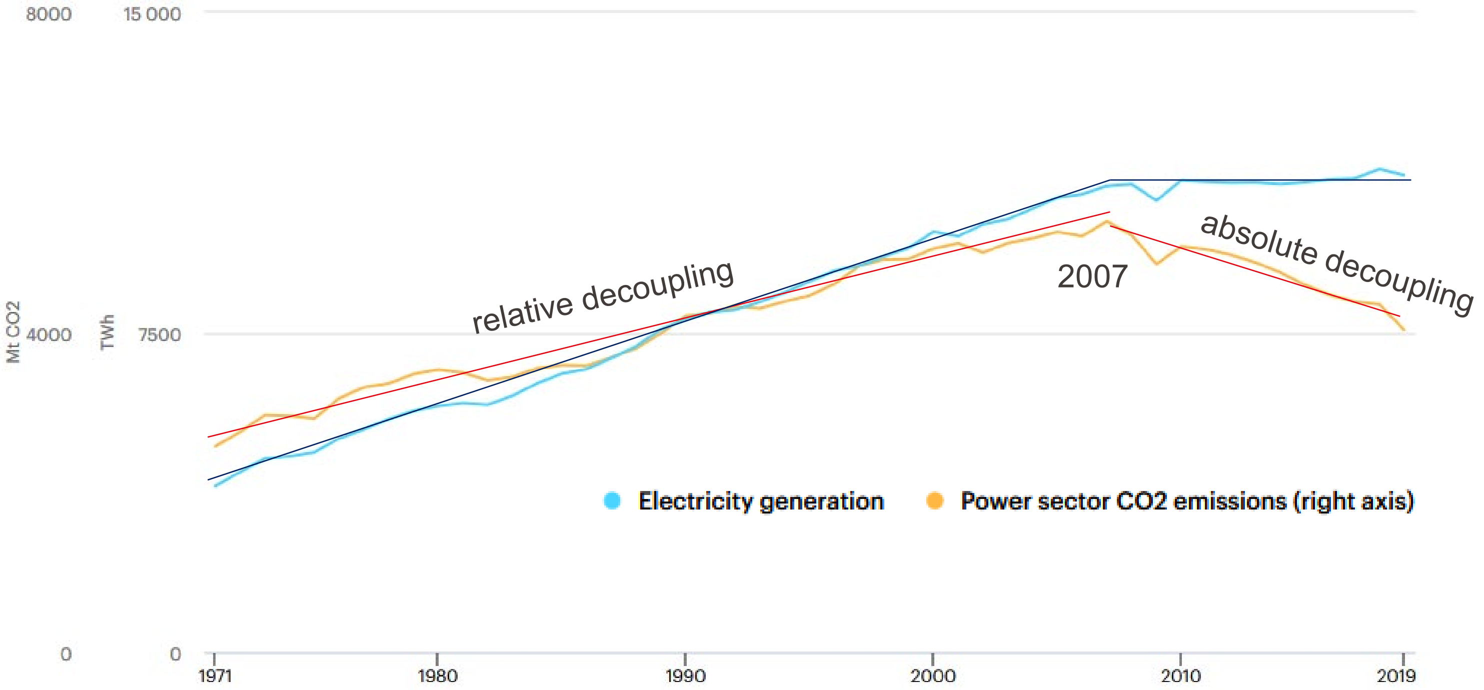
https://www.iea.org/data-and-statistics/charts/electricity-generation-and-power-sector-co2-emissions-in-advanced-economies-1971-2019

*Advanced economies: Australia, Canada, Chile, European Union, Iceland, Israel, Japan, Korea, Mexico, Norway, New Zealand, Switzerland, Turkey, and United States

Concept and importance

- Relationship between some activity and some resource use or some environmental impact
- When the use of the resource increases, but less than the activity → **relative decoupling**
- When the use of the resource decreases while the activity, increases → **absolute decoupling**

Relative and absolute decoupling



https://www.iea.org/data-and-statistics/charts/electricity-generation-and-power-sector-co2-emissions-in-advanced-economies-1971-2019

Why we love decoupling…

Eat More Food To Lose More Weight!

Losing weight isn't about skipping meals. Learn how to shed unwanted fat the right way, and eat more in the process.

NUTRITION

- RECIPES
- MEAL PLANNING
- DIET PLANS
- CALCULATORS
- NUTRITION TIPS
- SUPPLEMENTATION

Jamie Alderton with Lara McGlashan
September 20, 2018 • 7 min read

https://www.bodybuilding.com/content/eat-more-food-to-lose-more-weight.html, 24 March 2020

Lessons learned

- Decoupling harbours the possibility to sustain economic growth while shrinking environmental impacts
- It comes in a weak form (relative decoupling) and a strong form (absolute decoupling)
- Absolute decoupling is much easier when the underlying activity causing the impact grows more slowly

Conditions for decoupling

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Simple decomposition

$$\text{Impact} = \text{Activity} \times \frac{\text{Impact}}{\text{Activity}}$$

- Impact could be environmental emissions or some resource use
- Impact/Activity = **resource intensity**
- If Impact = CO_2 emissions, Impact/Activity = CO_2 intensity

Decomposition of the growth rate of CO_2 emissions from freight transportation in Switzerland, 1990-2023

		1990	2023	2023/1990
Activity	Freight transported (million t×km)	20 569	27 785	1.35
Impact / Activity	CO_2 per t×km of freight (kg)	0.118	0.097	0.82
Impact	**CO_2 emissions (million tons)**	**2.43**	**2.70**	**1.11**

Data from Fed. off. of statistics & of the environment

Intensity and efficiency

$$\text{Impact} = \text{Activity} \times \frac{\text{Impact}}{\text{Activity}} = \frac{\text{Activity}}{\text{Activity}/\text{Impact}}$$

- Activity/Impact = **resource efficiency** (inverse of intensity)
- If Impact = energy use, Activity/Impact = energy efficiency
- It is generally more convenient to work with intensity than with efficiency
- An increase in efficiency means a decrease in intensity

Intensity and efficiency – example

Decomposition of the growth rate of energy consumption for freight transportation in Switzerland, 2000-2023

		2000	2023	2023/2000
Activity	Freight transported (million t×km)	24 689	27 785	1.13
Impact / Activity	Energy per t×km of freight (MJ)	1.68	1.47	0.88
Impact	**Energy consumption (TJ)**	**41 361**	**40 852**	**0.99**

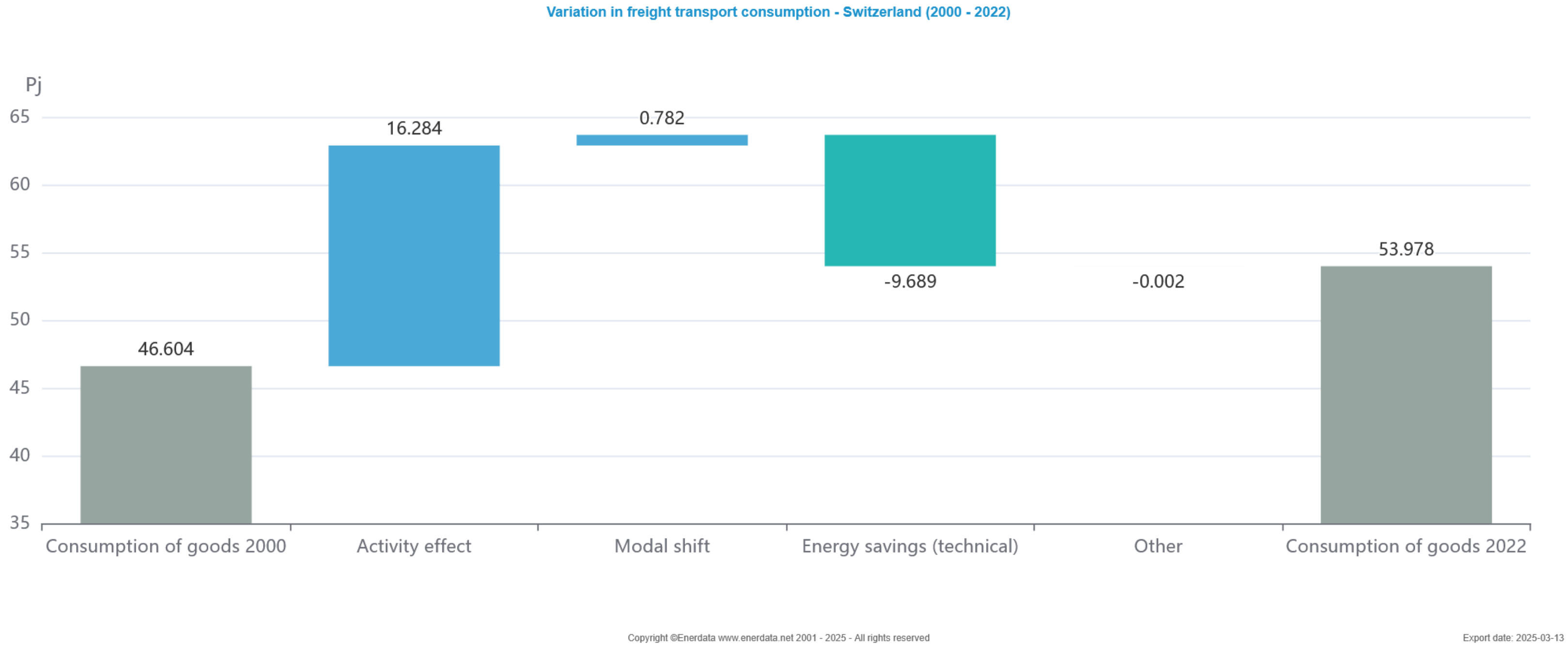
Data from Fed. off. of statistics & of energy

		2000	2023	2023/2000
Activity	Freight transported (million t×km)	24 689	29 472	1.19
Activity / Impact	Freight per MJ energy (t×km)	0.60	0.69	1.14
Impact	**Energy consumption (TJ)**	**41 361**	**40 852**	**0.99**

- In the first table, Activity × Intensity = Impact
- In the second table, Activity / Efficiency = Impact

Decomposition of Swiss energy consumption for freight transport

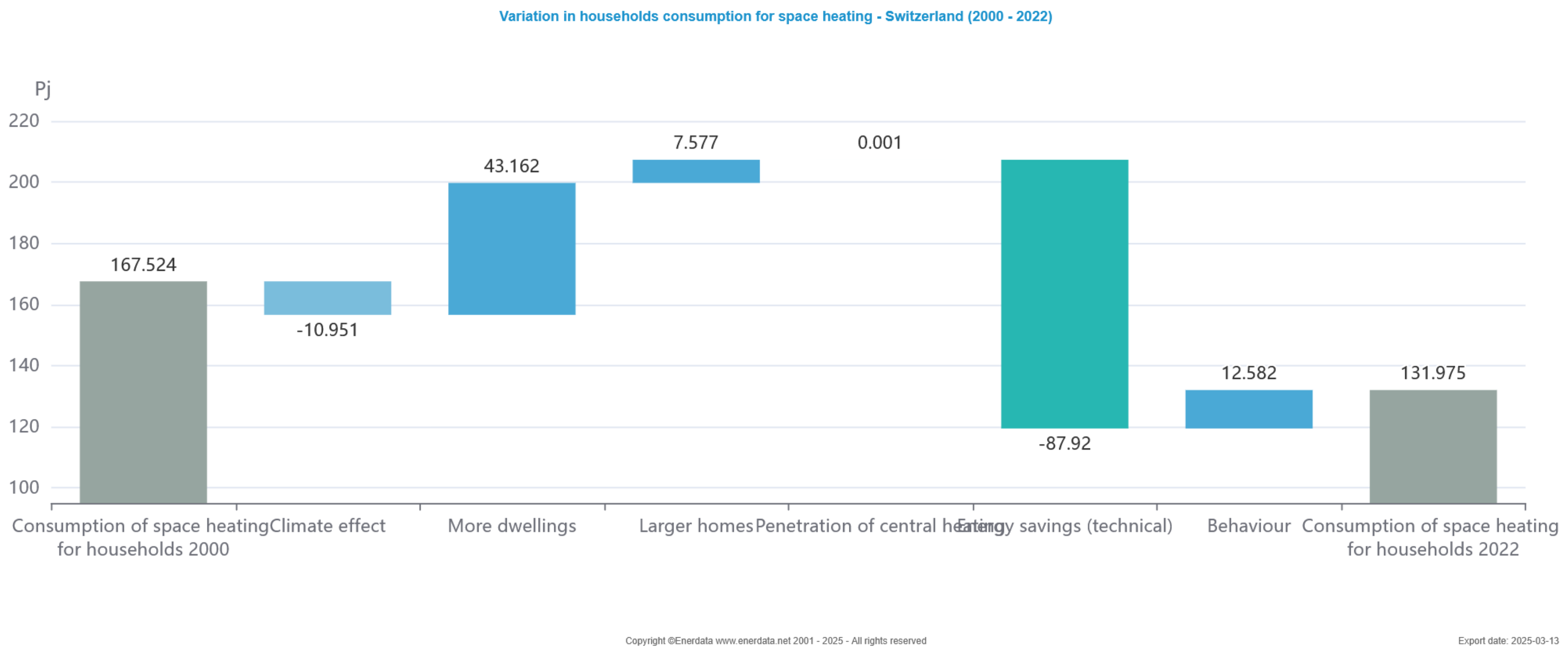
https://www.indicators.odyssee-mure.eu/decomposition.html, 13.03.2025



"Waterfall graph". Activity is measured in ton×km. Each component is expressed as the change in energy consumption it would have caused absent the other effects. Beware: the y-axis does not start from 0.

Decomposition of Swiss energy consumption for heating in housing

https://www.indicators.odyssee-mure.eu/decomposition.html, 13.03.2025



"Waterfall graph". Each component is expressed as the change in energy consumption it would have caused absent the other effects. Beware: the y-axis does not start from 0.

Link between efficiency and decoupling

- Efficiency is measured by how much 'service' or 'activity' is obtained with a given quantity of resource
- E.g. fuel efficiency of cars: number of miles per gallon of gasoline
- When fuel efficiency increases, gasoline consumption **increases less** than total miles driven
- With strong increase of fuel efficiency, gasoline consumption could even **decrease** despite more total miles driven

Relative and absolute decoupling

$$\text{Impact} = \text{Activity} \times \frac{\text{Impact}}{\text{Activity}}$$

Relative decoupling

- Impact grows, but at a smaller rate than Activity
- Resource intensity (Impact/Activity) decreases, but less than growth in Activity
- Resource efficiency (Activity/Impact) increases, but less than growth in Activity

Absolute decoupling

- Impact decreases, despite the growth of Activity
- Resource intensity (Impact/Activity) decreases more than growth in Activity
- Resource efficiency (Activity/Impact) increases more than growth in Activity

When activity is measured by GDP

$$I = GDP \times \frac{I}{GDP}$$

$$g_I \cong g_{GDP} + g_{I/GDP}$$

g are growth rates

- I = environmental impact
- I/GDP is the environmental or resource intensity of the economy
- If I is energy use, I/GDP is the **energy intensity** of the economy
- Assume that $g_{GDP} > 0$
- Relative decoupling: $0 < g_I < g_{GDP}$ because $-g_{GDP} < g_{I/GDP} < 0$
  e.g.: $g_{GDP} = 5\%$, $g_{I/GDP} = -2\% \rightarrow g_I = 3\%$
- Absolute decoupling: $g_I < 0$ because $g_{I/GDP} < -g_{GDP} < 0$
  e.g.: $g_{GDP} = 5\%$, $g_{I/GDP} = -6\% \rightarrow g_I = -1\%$

IPAT and Kaya decomposition

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IPAT formula

In 1971/72, Paul Ehrlich and John Holdren published their famous IPAT formula:

Environmental **I**mpact =
Population × **A**ffluence × **T**echnology

$$I = Pop \times \frac{GDP}{Pop} \times \frac{I}{GDP}$$

History of IPAT

Critique by Paul R. Ehrlich and John P. Holdren of Barry Commoner's 1971 book *The Closing Circle.* The critique, circulated in 1971 and published in 1972 in *Environment* and in *Bulletin of Atomic Scientists*, is reproduced here from John P. Holdren, A brief history of "IPAT" (impact = population x affluence x technology), *The Journal of Population and Sustainability* Vol 2, No 2, 2018, 63-65

Commoner admits that the factors contributing to environmental impact are multiplicative, rather than additive; he offers (in a footnote to pp 211-212) the equation

pollution = (population) x (production/capita) x (pollution emission/production)

Here the second factor on the right, production per capita, is in some sense a measure of affluence, and the last factor, pollution per unit of production, is a measure of the relative environmental impact of the technology that provides the affluence. For compactness, let us rewrite this equation

$$I = P \times A \times T \qquad (1)$$

or, in terms of initial values and the subsequent changes, over a specified period of time,

$$I + \text{delta } I = (P + \text{delta } P) \times (A + \text{delta } A) \times (T + \text{delta } T) \qquad (2)$$

Here I is for impact (a better word than "pollution" for reasons already explained), P is for population, A for affluence, and T for technology. Le

IPAT for primary energy consumption in UK 1820-2023

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$$E = Pop \times \frac{GDP}{Pop} \times \frac{E}{GDP}$$

E = primary energy consumption

	1820	2023	Growth factor	Equiv. yearly growth rate*
Population ('000)	20 707	68 683	3	0.59%
GDP/capita (USD2011)	3 306	38 222	12	1.21%
Energy/GDP (kWh/USD2011)	2.56	0.74	0.29	−0.61%
Energy consumption (TWh)	175	1 931	11	1.19%

* Defined so that $V_{1820} \times (1+g)^{2023-1820} = V_{2023}$

Data: Maddison Project Database 2023, Our World in Data, and UK National Infrastructure Commission

Thanks to division by 3 of energy intensity of GDP, primary energy consumption was 'only' multiplied by 11 when economic activity was multiplied by 36

Calling I/GDP 'technology' is a bit of a stretch

Determinants of I/GDP (e.g. E/GDP):

- Composition of GDP: what is produced, e.g., agricultural commodities, industrial goods, services
- Modes of production: labour- or capital-intensive, small-scale decentralised or large-scale concentrated
- Choice of 'machinery': energy vector, energy efficiency
- Mode of operation of 'machinery': conservative or wasteful

IPAT for CO_2: Kaya decomposition

$$\mathrm{CO_2}\ emissions = Pop \times \frac{GDP}{Pop} \times \frac{E}{GDP} \times \frac{CO_2}{E}$$

E is energy consumption (primary or final)

Yiochi Kaya is a Japanese energy economist

He proposed this formula in 1993

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Improvements in energy use and mix cancelled by economic and population growth

$$\mathrm{CO_2}\ emissions = Pop \times \frac{GDP}{Pop} \times \frac{E}{GDP} \times \frac{CO_2}{E}$$

$$\%\mathrm{CO_2} = \%Pop + \%(GDP/Pop) + \%(E/GDP) + \%(CO_2/E)$$

Decomposition of the average annual growth rate of global energy-related CO_2 emissions since the 1st oil price shock

	1965-1973	1973–1990	1990–2010	2010-2023
Population	2.1%	1.8%	1.4%	1.1%
GDP/population	3.0%	1.3%	1.6%	1.7%
Total primary energy cons./GDP	-0.4%	-0.9%	-1.0%	-1.2%
CO_2 emissions/TPEC	0.1%	-0.6%	-0.1%	-0.6%
CO_2 emissions from energy	4.8%	1.6%	1.9%	0.9%

Sources of data: World Bank and Energy Institute

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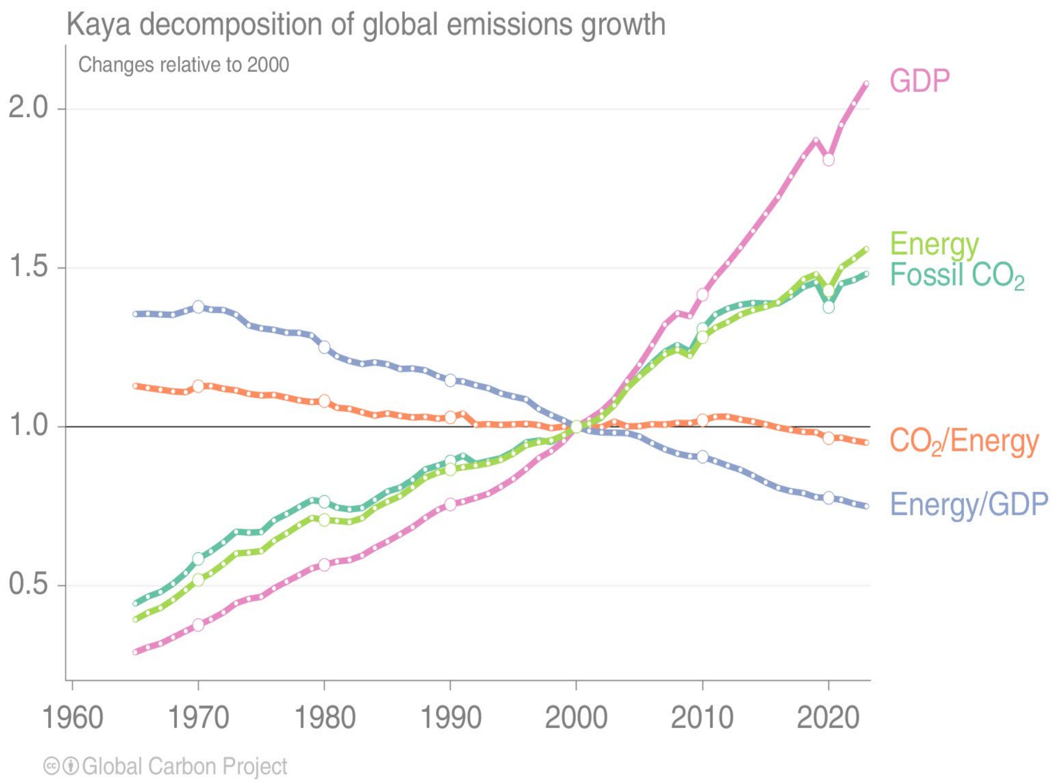
Kaya decomposition for global CO_2 emissions



"Global Carbon Budget 2024" presentation

This Kaya decomposition shows that decreasing energy intensity (energy/GDP) was more important than decarbonisation of energy for the relative decoupling of CO_2 emissions form GDP

Kaya by region

- In China as in EU27, population growth played nearly no role
- In China and India, GDP/capita growth was the main driver
- Nearly everywhere, energy/GDP decreased
- Decreasing CO_2/energy is more recent

"Global Carbon Budget 2024" presentation

Objectives / desirable evolution

Necessary reduction in the CO_2 intensity of energy so that global CO_2 emissions decrease by 48% relative to 2021 by 2030

	2023-2030		without economic growth	
	factor	%/year	factor	%/year
Population	1.07	0.9%	1.07	0.9%
GDP/capita	1.13	**1.8%**	1.00	**0.0%**
GDP	*1.21*	*2.8%*	*1.07*	*0.9%*
Energy/GDP	0.81	**-3.0%**	0.81	**-3.0%**
Energy	*0.98*	*-0.3%*	*0.86*	*-2.1%*
Target for CO2 emissions	**0.50**	-9.3%	**0.50**	-9.3%
Needed reduction of emissions by unit of energy	0.52	-9.0%	0.58	-7.4%

$$\%(CO_2 / Energy) = \%CO_2 - \%Pop - \%(GDP / Pop) - \%(Energy / GDP)$$

Population: UN 2022 forecast; GDP/capita growth = mean of 2010-2019 (pre-Covid); Energy/GDP: COP28 Global Renewables and Energy Efficiency Pledge; Target for CO2 emissions: Mean estimate of reduction needed to limit warming to 1.5°C (>50%) with no or limited overshoot (IPCC AR6 Synthesis Report Table SPM.1)

Cross-sectional IPAT

- The IPAT framework can be used to compare countries
- Example: Kaya for France and United Kingdom

Decomposition of difference in CO_2 emissions between France and UK, 2021

KAYA		France	UK	UK/France
Population	Million	64.53	67.28	1.043
GDP/Population	Int. USD2017	47 265	45 036	0.953
Energy/GDP	GWh/billion USD	856	660	0.771
CO_2/energy	kg/kWh	0.150	0.211	1.407
CO_2 emissions	Million tons	**390.8**	**420.9**	**1.077**

Finer decomposition of CO_2 emissions

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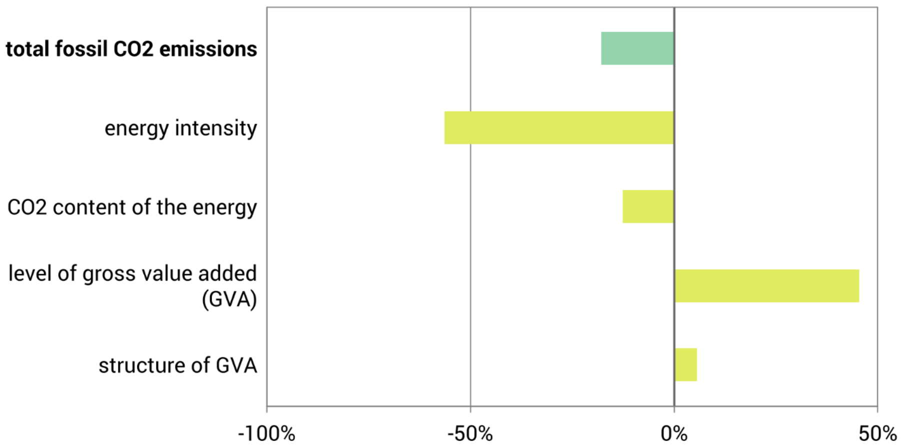
$$CO_2 = GDP \times \sum_j \frac{Prod_j}{GDP} \times \frac{E_j}{Prod_j} \times \frac{CO_{2j}}{E_j}$$

- $Prod_j$ is production of sector j, changing with economic growth and product shifts (sufficiency, structural changes)
- $E_j/Prod_j$ is energy intensity in sector j, changing with energy efficiency
- CO_{2j}/E_j is carbon intensity of energy in sector j, changing with energy substitution (electrification, syn. fuels, renewable heat) and carbon capture and sequestration

Factors influencing the development of CO2 emissions of the economy
Change between 2000 and 2022



Source: FSO – Environmental accounting

Other example for a Kaya decomposition – Heating

CO_2 emissions from heating =

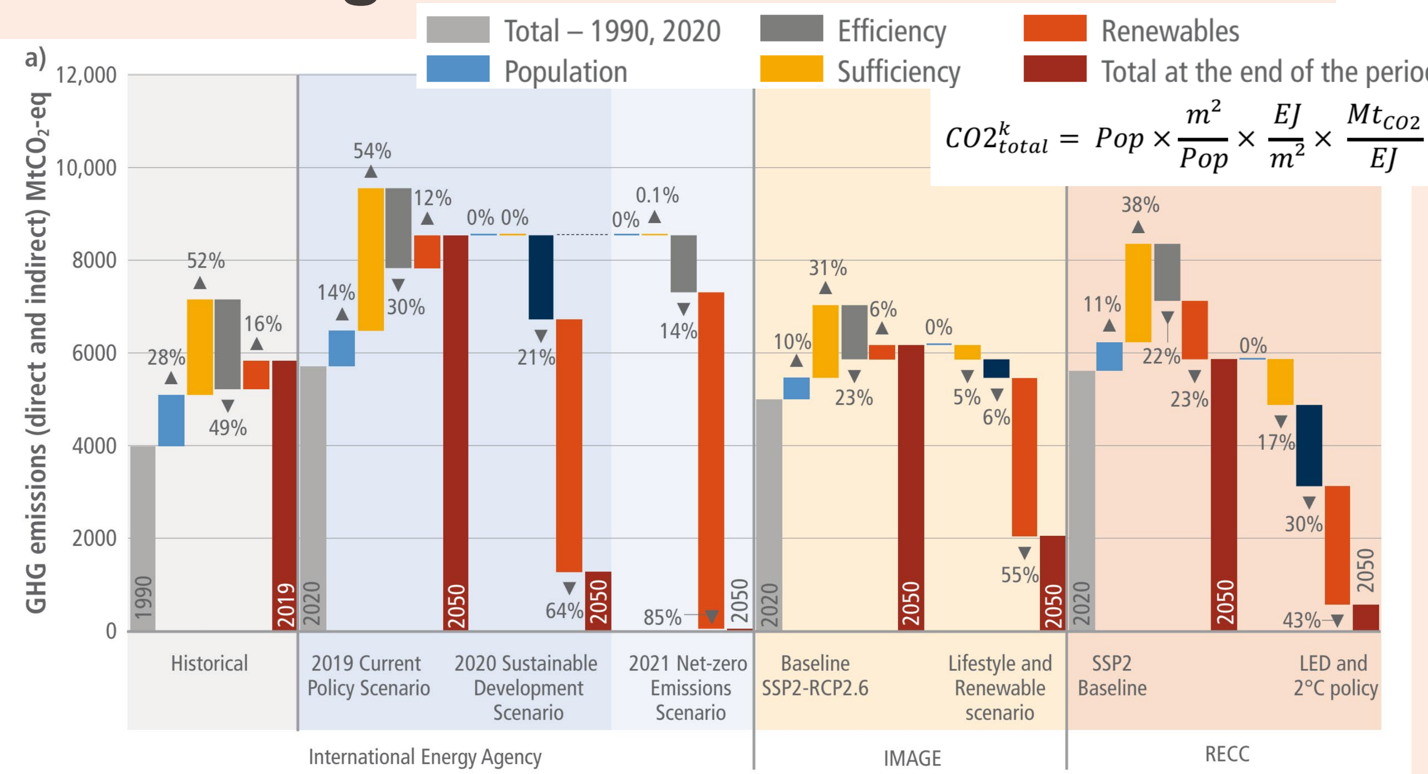
Population

× (total heated housing surface / population)

× (energy used for heating / total heated housing surface)

× (CO_2 emissions from heating / energy used for heating)

Other example for a Kaya decomposition – Heating



$$CO2^{k}_{total} = Pop \times \frac{m^2}{Pop} \times \frac{EJ}{m^2} \times \frac{Mt_{CO2}}{EJ} = Pop \times Suff \times Eff \times Ren$$

'Sufficiency' = increase in m^2 per capita of total floor area

Figure 9.5 | Decompositions of changes in historical residential energy emissions 1990–2019, changes in emissions projected by baseline scenarios for 2020–2050, and differences between scenarios in 2050 using scenarios from three models: IEA, IMAGE, and RECC. RECC-LED data include only space heating and cooling and water heating in residential buildings (a) global resolution, and (b) for nine world regions.

IPCC AR6 WG III, Chap. 9, pp. 967-8

Lessons learned

- IPAT and Kaya evidence the separate contributions of demographics, economic growth and technological choices on environmental impacts, in particular CO_2 emissions
- It is extremely difficult to obtain enough efficiency improvement and resource substitution to offset economic and population growth and reduce environmental impacts

https://www.treehugger.com/forget-efficiency-it-time-get-serious-about-sufficiency-4854770

Efficiency
Substitution
Sufficiency

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Avoid, improve, shift
Sufficiency, efficiency, substitution

$$\mathrm{CO_2}\ emissions = Activity \times \frac{Energy}{Activity} \times \frac{CO_2}{Energy}$$

- Reduce **Activity**: avoid energy use, aim for sufficiency in activity
- Reduce **Energy/activity**: improve energy efficiency
- Reduce **CO_2/Energy**: shift to or substitute by lower-emissions energy

Sufficiency, efficiency, substitution everywhere

$$CO_2 \ \ emissions\ from\ mobility = Mobility \times \frac{Energy}{Mobility} \times \frac{CO_2}{Energy}$$

- The distinction between the three levers is not as clear-cut as might appear from this decomposition
- There is 'sufficiency' in choosing low-energy options for mobility (small fuel-efficient cars, active mobility) and in opting for the more expensive clean energy
- There is 'efficiency' in organising one's life to carry on with less mobility
- There is 'substitution' in replacing daily commutes by remote working, and personal cars by public transportation

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Using the confusion as a force (1)

- Consider reducing the speed limit on highways
- This reduces energy use, air pollution, accidents and congestion for nearly the same 'service' at nearly zero cost (negative cost if counting the fuel economy)

https://www.roadangelgroup.com/news/smart-motorways-and-variable-speed-limits/

- It can be sold as an <u>efficiency</u> measure: you get the same mobility with less resources and congestion time
- It can be sold as a <u>sufficiency</u> measure: do you need that speed?

Using the confusion as a force (2)

- Consider tiny apartments or tiny houses
- Fewer m^2 per person reduces material, energy, and space use

Microcosmos living in Chur (GR)

- This can be sold as an efficiency measure: the volume of a building is much better used to host more people
- This can be sold as a sufficiency measure: how many m^2 do you really need for good living?

Using the confusion as a force (3)

- Consider replacing ICE by electric motorcycles
- EVs use less energy and produce less air pollution and noise, at moderately higher lifetime cost

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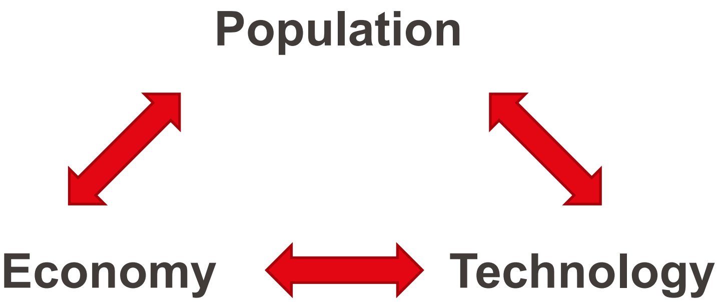
- This can be sold as a substitution measure: you get the same mobility with clean energy
- This can be sold as an efficiency measure: you get the same mobility with less energy
- This can be sold as a sufficiency measure: do you need that roaring engine?

How to define 'Sufficiency' ?

- Sufficiency is when you renounce some good or service not because you do not like it, cannot afford it, are not allowed to buy it or do not have the time for it, but only because it is harmful for the environment
- It is the motive and not the act that characterises sufficiency
- Sufficiency is particularly important for the wealthiest, because hardly anything else can lower their environmental footprint



Limitations of IPAT and Kaya

Diversity

Interactions

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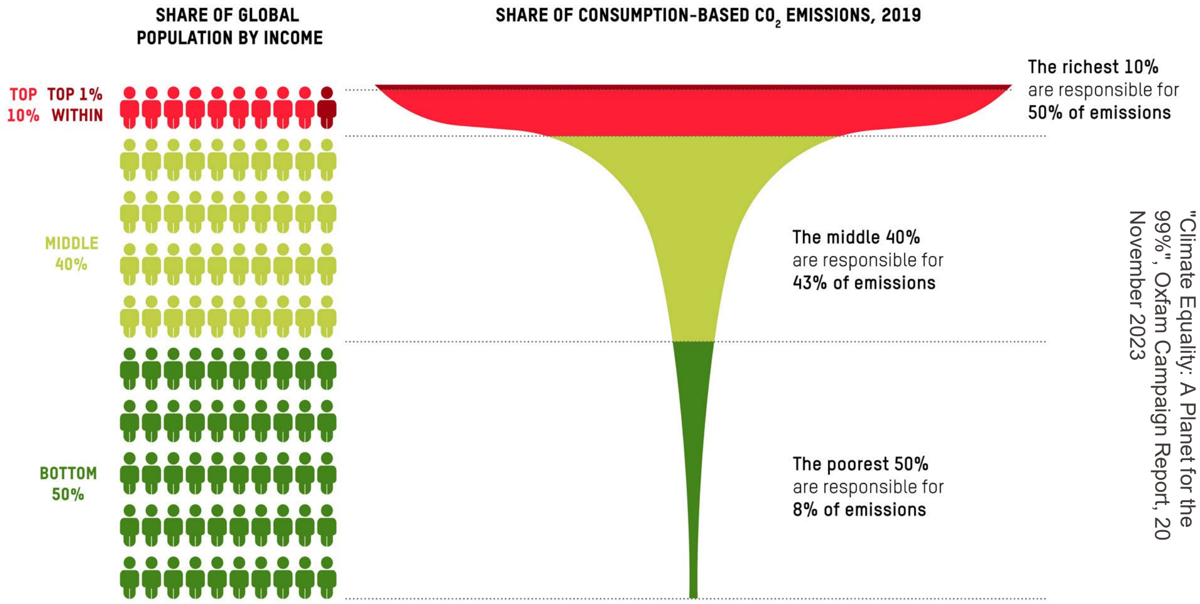
Limitation of IPAT
Diversity hidden behind aggregates

$$I = Pop \times \frac{GDP}{Pop} \times \frac{I}{GDP}$$

- A common recommendation to lower I, derived from IPAT or not, is to slow population growth
- But, there is huge variety in impact per capita

Consumption-based CO_2 emissions by income group, worldwide



"Climate Equality: A Planet for the 99%", Oxfam Campaign Report, 20 November 2023

Limitation of IPAT-like decompositions : Diversity hidden behind aggregates

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2020	Qatar	Congo, Dem. Rep.	Total	Qatar	Congo, Dem. Rep.
Population (million)	2.9	89.6	92.4	3%	97%
GDP per capita (thousand current PPP USD)	90.0	1.1			
CO_2 emission intensity (kg/USD)	0.41	0.02			
CO_2 (million tons)	106.7	2.5	109.1	98%	2%
CO_2 per capita (tons)	*37.02*	*0.028*			

Own calculations with data from World Bank and Our World in Data

- This illustrates how a small wealthy country can account for a disproportionate share of global environmental impact
- The average Qatari emits as much as 1300 Congolese…
- Slowing population growth in DR Congo would change little to global emissions
- It could, however, reduce the pressure on local ecosystems in DR Congo

Limitation of IPAT: it is nearly impossible to move the levers separately

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The P, A, T components are seen as levers when one tries to influence them with a view to lowering I

But, can these levers be moved independently?

Intuition :

- Decomposition: Distance covered running = running time × average speed
- Running longer allows covering a longer distance: run twice as long to run twice as far?
- In fact, you can hardly increase running time without loss of speed (if a racer covering 100 m in 10" could keep that speed for 1h10', he would run a record marathon)

Limitation of IPAT: it is nearly impossible to move the levers separately

Example (exhaustion):

- Oil extracted from a well = extraction time × average extraction rate
- The first days of extraction allow a high extraction rate, but as the well dries up, the extraction rate dwindles
- Increasing the extraction rate shortens the maximum extraction time

Example (crowding out):

- Energy used in buildings = building area × energy per m^2
- When the building area grows relatively rapidly, little resources are left to improve the energy efficiency of existing buildings

Example (rebound):

- Energy used by cars = km driven × energy per km
- Lowering energy/km lowers the cost of driving, which encourages more driving

Interactions between levers

Environmental Impact =
Population × **A**ffluence × **T**echnology

$$I = Pop \times \frac{GDP}{Pop} \times \frac{I}{GDP}$$

- Demographics: A → P through fertility
- Planetary boundaries: I → A through worsening production and living conditions
- Resource availability: A → T as more activity may require using ‘dirtier’ resources as not enough of the ‘clean’ resources are available
- Environmental Kuznets Curve: A → T as cleaner options become more desirable and affordable
- **Green growth**: T → A through new markets and jobs
- **Rebound**: T → A as resource efficiency lowers usage cost and increases purchasing power

Lessons learned

IPAT is powerful analysis tool, but it must be used with care:

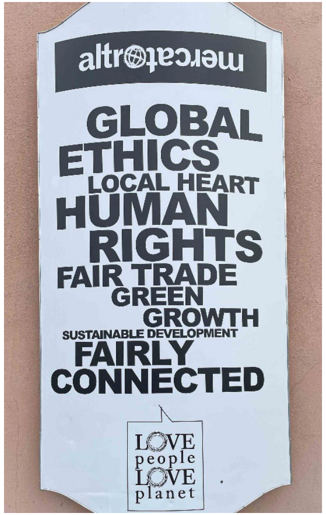
- The decomposition needs to make sense, i.e., all components (ratios) need to have a real meaning
- The change of a component need not cause a one-to-one change in the impact
- The levers cannot always be moved individually, without affecting the other ones
- Particularly the population lever must be moved with care and pointing at population growth as the main source of environmental problems is often wrong

Green growth

Philippe Thalmann

whygreeneconomy.org

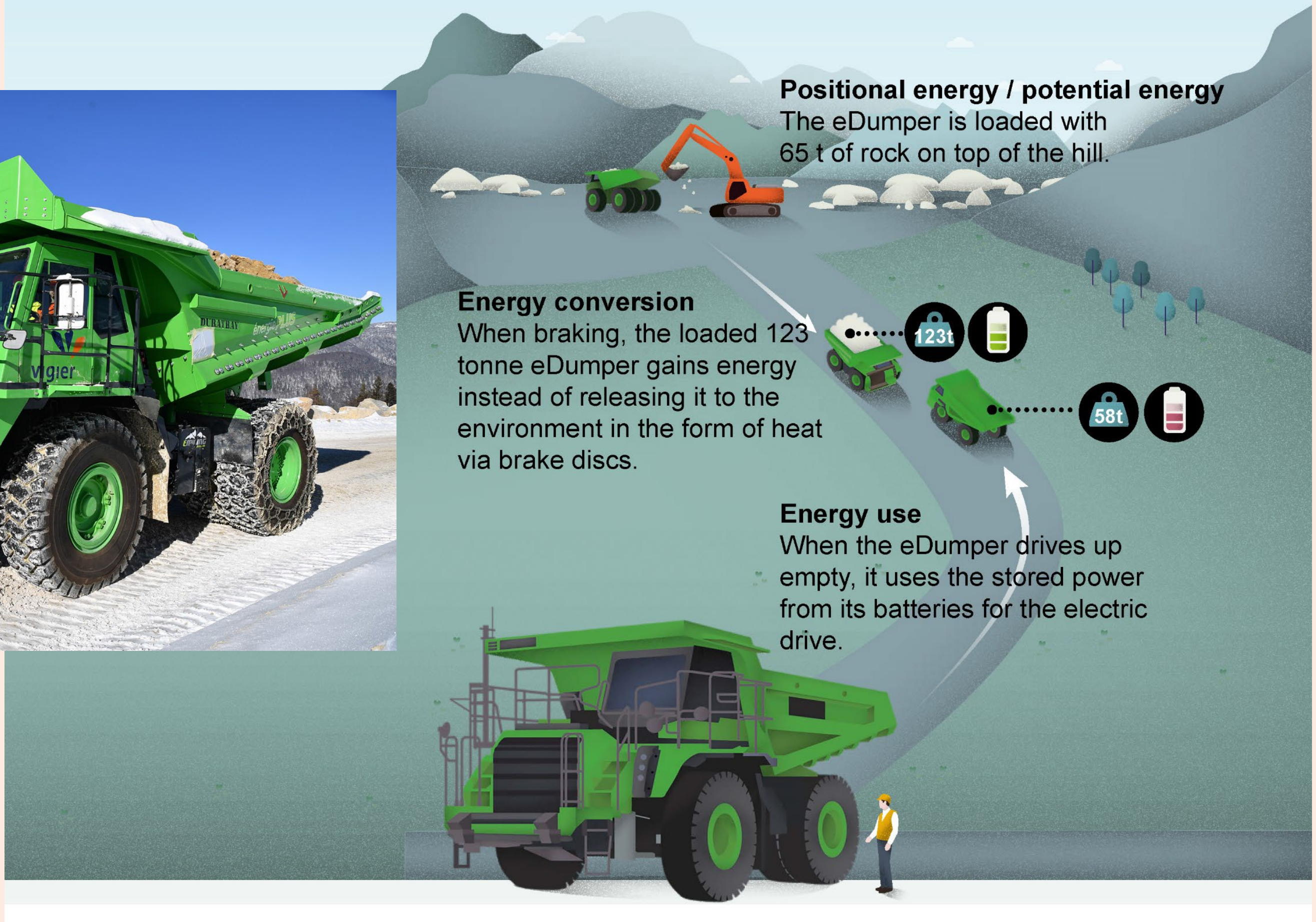
Buzzwords…



Saving the world could be good for economic growth

- The promise of **cleantech**: new products, new sectors, new jobs
- **First mover advantage**: countries that develop their cleantech first can conquer world markets as other countries follow suite ('Porter hypothesis')

Smart electric truck



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https://www.wbf.admin.ch/wbf/en/home/dokumentation/nsb-news_list.msg-id-70487.html

Green growth could be an illusion at best, a diversion at worst

- What happens to the investments and jobs in 'dirty tech'?
  → stranded assets
- In effect, 'green' production is an addition to rather than a replacement of 'dirty' production
- When 'green' only means 'non-fossil', green growth could just exacerbate other resource depletions and pollutions
- Green growth does not address all the other problems of economic growth (poverty, inequality, discrimination, social isolation, etc.), particularly if it is driven by the same actors of 'dirty' growth
- In short, 'green growth' is not to be confused with 'just transition'

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Rebound effect

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Origins of concept

- The rebound effect is also called Jevons' paradox, since Stanley Jevons had already observed in his book "The Coal Question" (1865) that efficiency gains in James Watt's steam engine actually led to increased consumption of coal and not to the reduction one might have expected
- The reason is that a machine's greater energy efficiency lowers the cost of the service it provides, so one uses it more
- E.g., driving more km with a more fuel-efficient car

W. Stanley Jevons (1835-1882)

EPFL

Example

- A house gets insulated to the effect that its heating energy use can be reduced by 60% for the same thermal comfort
- Its owners could save 60% on their heating bill
- It costs them much less to raise the average room temperature per additional 1°C
- So, they will increase the average room temperature and keep the windows open more often
- If the actual saving is only 40%
  → rebound effect = (60% – 40%) / 60% = 1/3
- Even greater rebound if they use the 40% saved on their heating bill to fly to a distant holiday destination

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More evidence on decoupling

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Converging evidence on insufficient decoupling

A survey* of 835 peer-reviewed articles that test decoupling of primary energy or useful exergy, CO_2 or greenhouse gas emissions, at global or national level, production or consumption-based finds:

- Relative decoupling is frequent for material use as well as GHG and CO_2 emissions but not for useful exergy
- Primary energy is decoupled from GDP largely through its more efficient conversion to useful exergy
- Examples of absolute long-term decoupling are rare, particularly consumption-based
- Large rapid absolute reductions of resource use and GHG emissions cannot be achieved through observed decoupling rates
- Hence, decoupling needs to be complemented by sufficiency-oriented strategies and strict enforcement of absolute reduction targets

*Haberl, H. et al (2020). "A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights." Environmental Research Letters 15:065003

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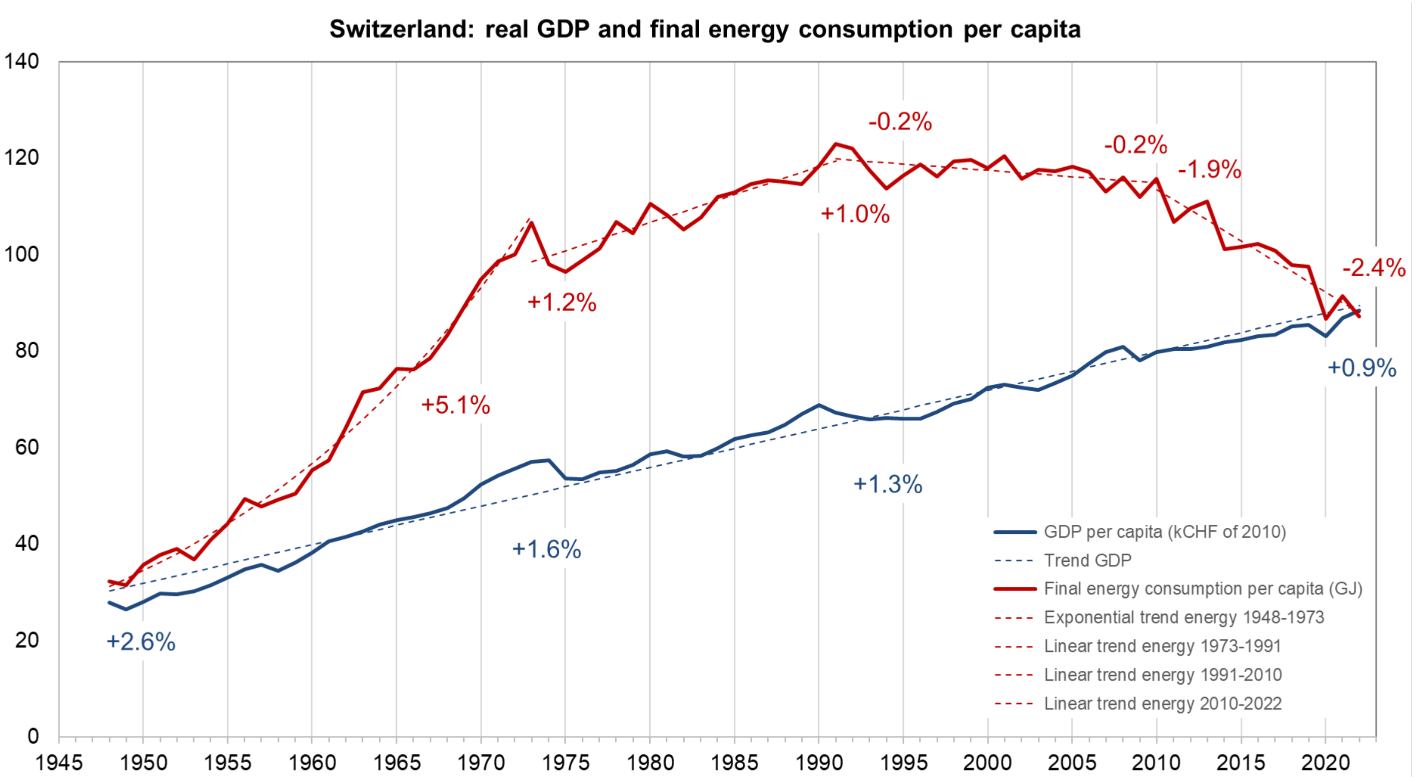
Decoupling of energy consumption in Switzerland



Source of data: Federal office of energy, Overall energy statistics, and Federal office of statistics

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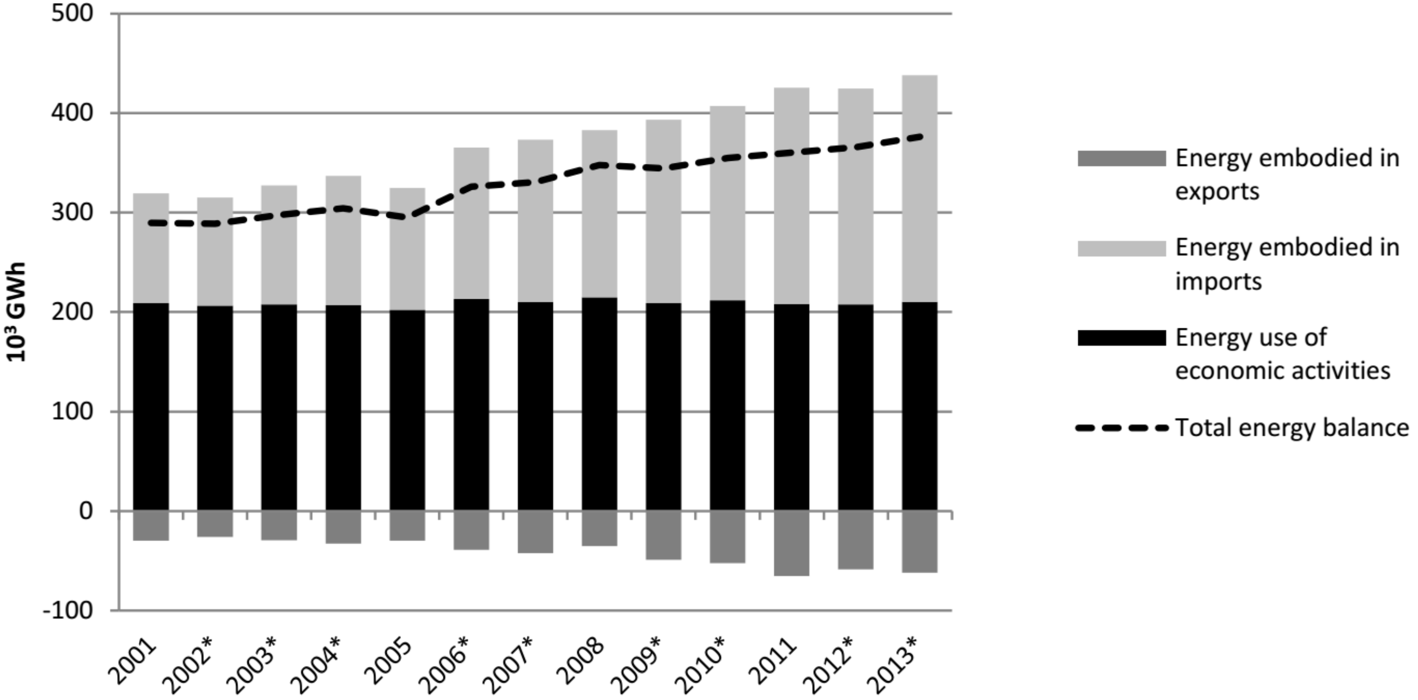
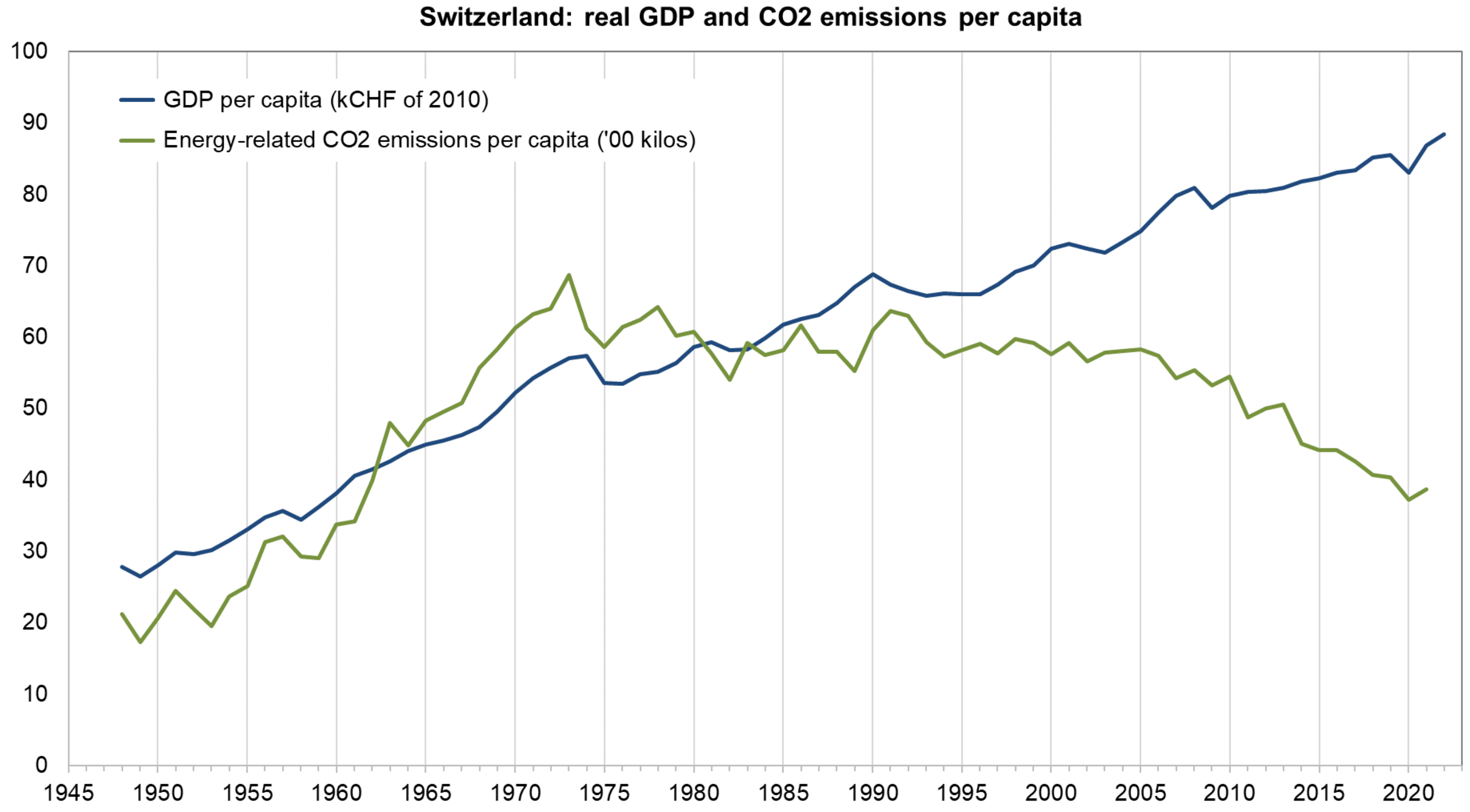
Decoupling obtained by globalisation



Moreau, V. and F. Vuille (2016). Decoupling energy use and economic growth: counter evidence from embodied energy in Swiss trade, EPFL Energy Center. * = inter/extrapolated

EPFL

Decoupling of CO_2 emissions in Switzerland



Source of data: Federal office of environment and Federal office of statistics

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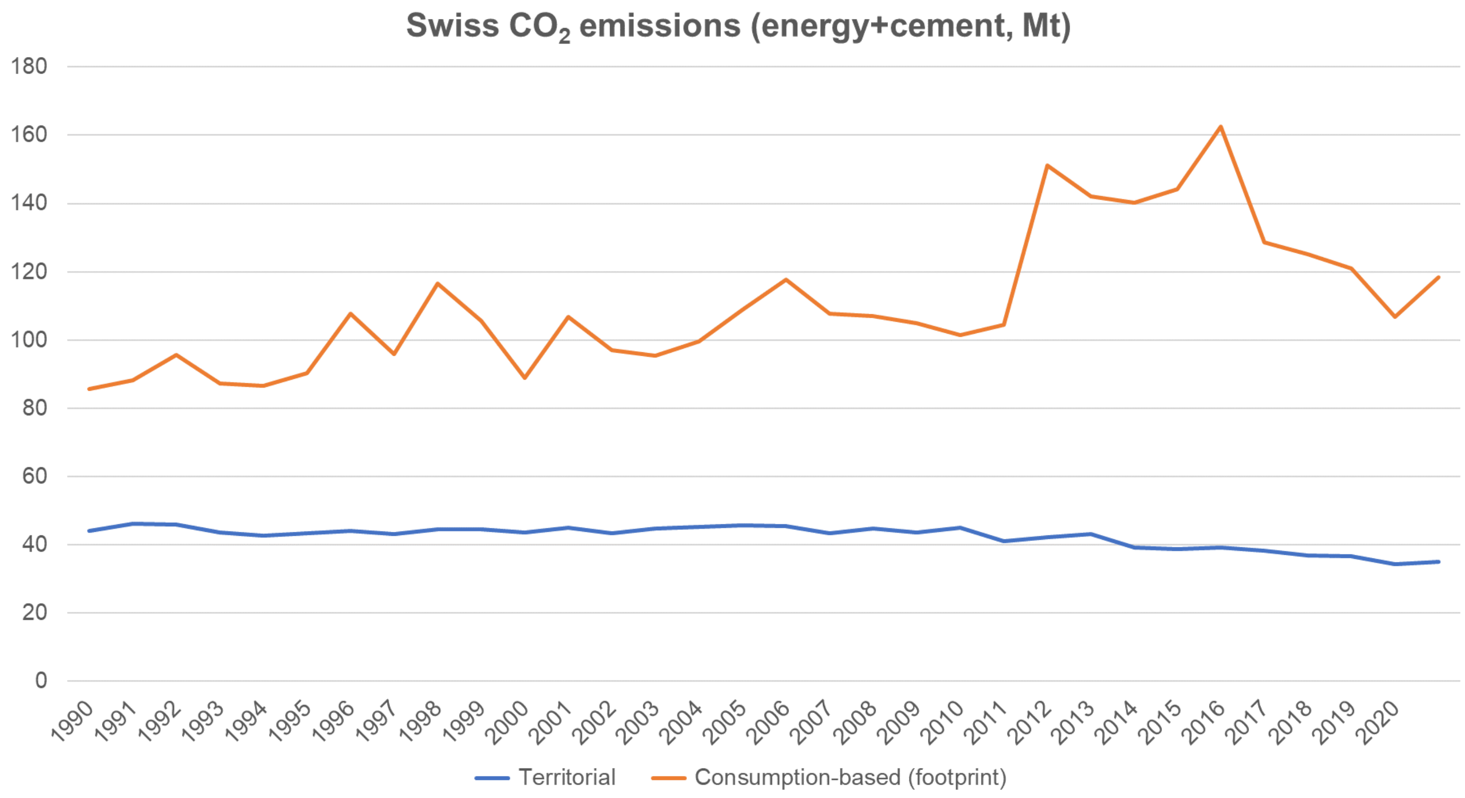
Decoupling obtained by globalisation (2)



Emissions from fossil energy and cement, data from Global Carbon Project database

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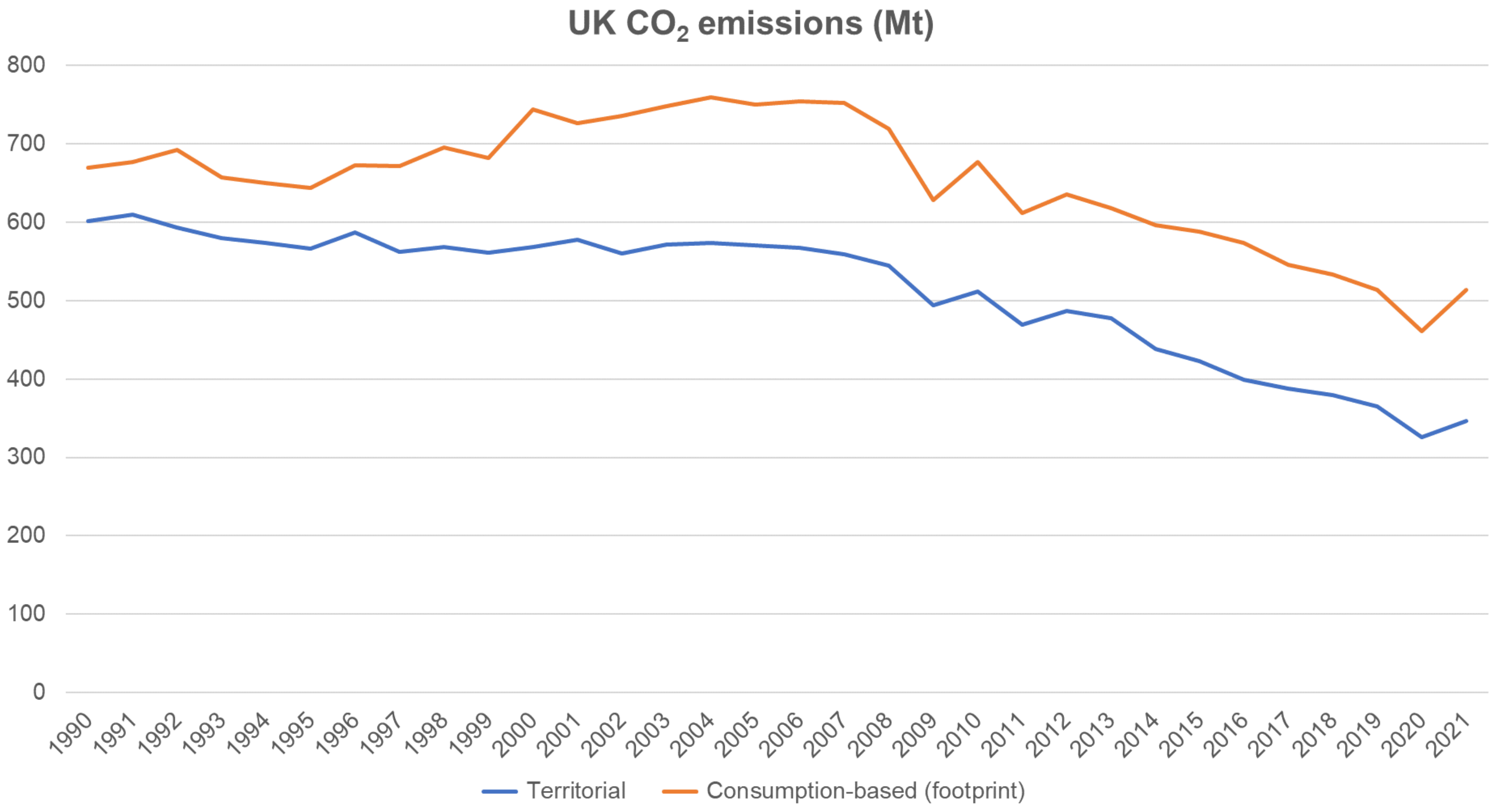
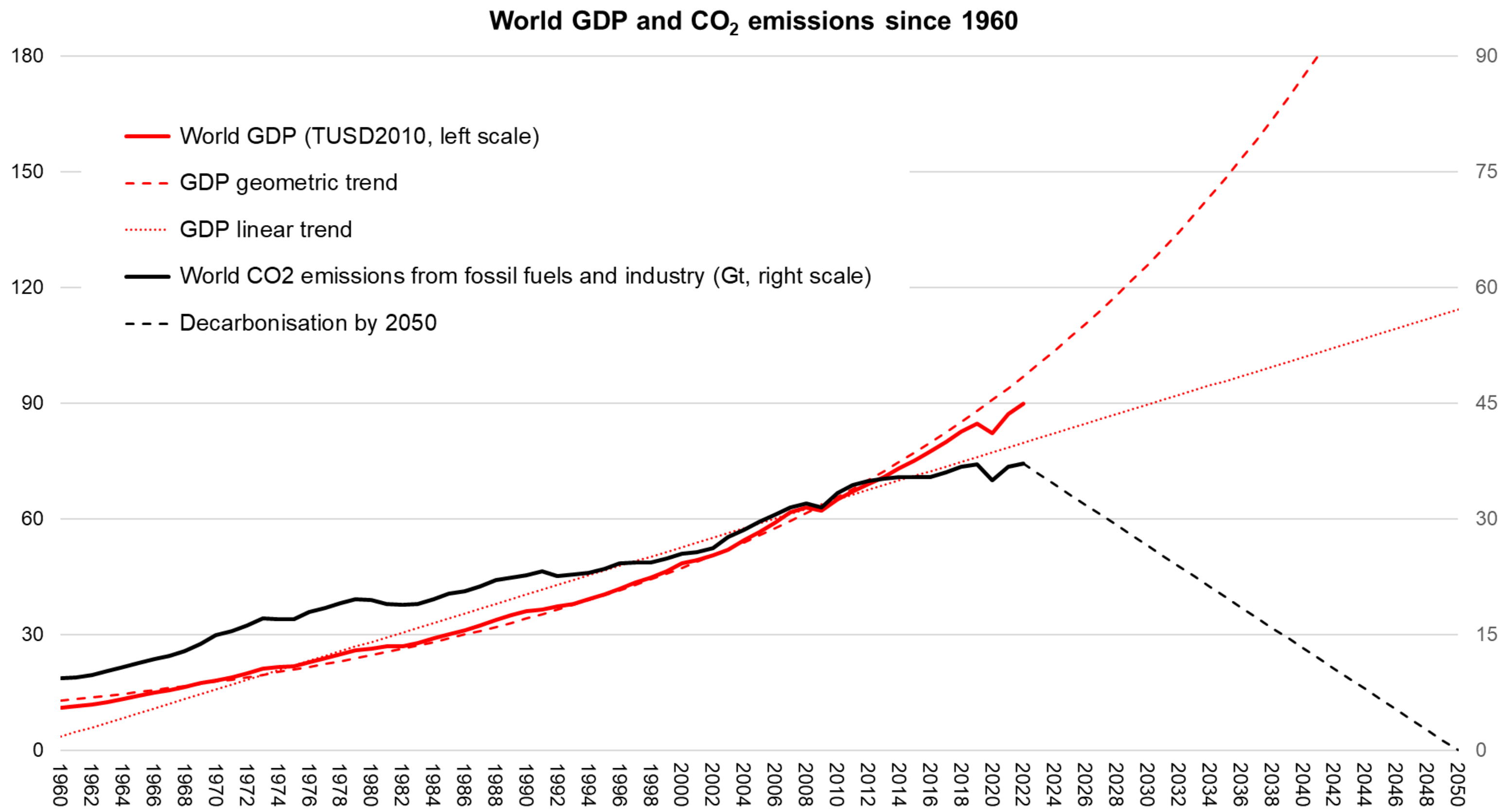
Decoupling despite globalisation



Emissions from fossil energy and cement, data from Global Carbon Project database

Worldwide GDP-CO_2 decoupling will be difficult



Own figure with data up to 2022 from World Bank and ICOS, Global Carbon Budget, 2023

Lessons learned

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- Absolute decoupling would allow the pursuit of two goals that seem contradictory: economic growth and the preservation of resources
- Relative decoupling is much less challenging, but not sufficient while the economy grows
- More advanced countries decoupled their energy use and CO_2 emissions from their economic growth, but they often did so by shifting 'dirty' production abroad
- Recessions or other economic shocks often caused the decrease in environmental impacts; this is not decoupling

Conditions for sustainable decoupling

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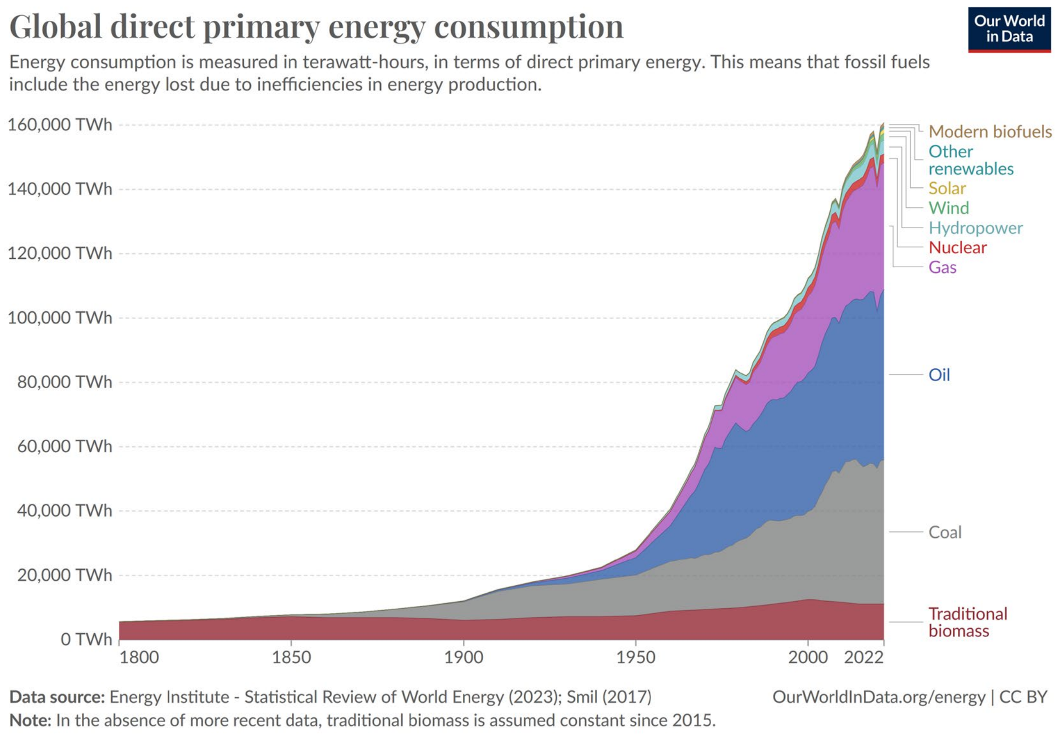
Conditions for sustainable decoupling (1)

1. Avoid shifting polluting activities to lower-income countries
2. Handle the environmental impacts of the 'green' alternatives
   - Land use and environmental burden of agrofuels
   - Minerals used for renewables and electric machines
   - Social, political and environmental risks of nuclear and large hydro-power generation
3. Tackle the rebound effect
   - Direct rebound (increased use of cheaper service)
   - Indirect rebound (damaging use of money saved)

Conditions for sustainable decoupling (2)

4. Make sure that there is real substitution and not just addition
   - Not renewable energy added to fossil energy
   - Not services added to the material economy



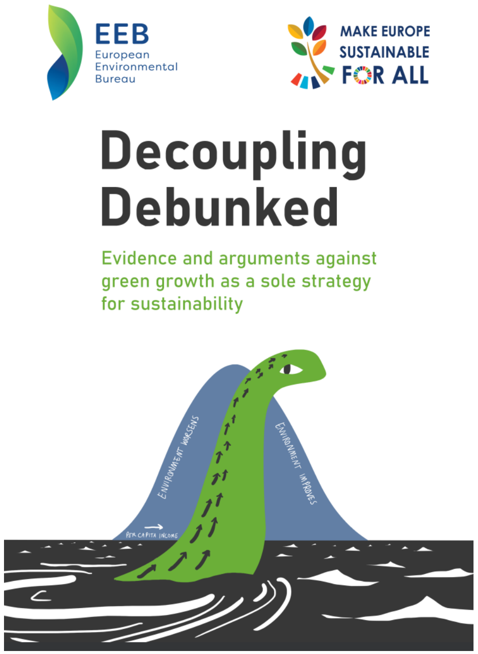
https://ourworldindata.org/grapher/global-primary-energy

Conditions for sustainable decoupling (3)

5. Do not ignore physical limits
    - Limits to recycling (circular economy)
    - Decreasing return on energy (low-cost resources are extracted first)
6. Make sure that technical progress improves rather than worsens the situation

Lessons learned

- Absolute decoupling would be nice: continued economic growth within the planetary boundaries
- There is evidence of decoupling … but only in some sectors or countries, often with offsetting increases in environmental impacts in other sectors or countries
- Decoupling does not come automatically with economic growth, it requires strong policies
- Conclusion: go for decoupling, but do not count on it to save the world → the myth of economic growth needs to be addressed



Parrique T., Barth J., Briens F., C. Kerschner, Kraus-Polk A., Kuokkanen A., Spangenberg J.H., 2019. Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability. European Environmental Bureau, eeb.org/decoupling-debunked