Kaya Identity exercice

Note : This exercice is inspired by the one created by Cédric Ware (`https://gitlab.telecom-paris.fr/cedric.ware`). It was modified by Sylvie Icart, Martine Olivi, Sylvain Chevillard, Luc Deneire and Guillaume Urvoy-Keller.

Introduction

Carbon neutrality (2050 objective of the Paris agreements) consists of capturing as many GHGs [1] as residual human activities will produce in 2050. To achieve carbon neutrality, we therefore have essentially two levers :

- reduce our GHG emissions,
- capture more GHGs - current sources and sinks are shown in figure 1.

Many avenues are being considered to achieve this neutrality, for example

- move away from fossil fuels ;
- accelerate technological innovation to improve energy efficiency or to develop capture techniques ;
- develop low-carbon energies (nuclear, renewable) ;
- deploy collective sobriety : significantly reduce the supply and demand for energy, manufactured products [2] ;
- rely on nature (nature-based solutions) and increase its absorption capacities of CO_2 .
- etc.

method	limit	compensate
ecological	sobriety, fair transition [1]	nature-based solutions
technological	decarbonized energies, energy efficiency	tech. carbon capture

To implement these "solutions", it is essential to put in place regulatory tools : financial tools (taxes/subsidies), interventionist laws (quotas, bans) ; as well as alternative narratives.

While each solution has its supporters who present it as "the solution", it is clear today that none is sufficient on its own. So, which ones should we favor ? How can we combine them ? The Kaya identity, due to Yoichi Kaya, gives us a small idea of the potential impact of these solutions on energy-related CO_2 emissions (about 2/3 of total GHG emissions).

Kaya identity and objectives of the practical work

The Kaya identity and its variants derive from a tautology [3] :

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{PIB} \times \frac{PIB}{POP} \times POP \tag{1}$$

With :

1. Greenhouse Gases.
2. See présentation du 04/04/23 by Sarah Thiriot for Labos1point5.
3. Several variants are possible depending on the factors that we choose to introduce into the identity, which determines a reading grid on the different levers of action. The choice made in identity (1) links emissions to energy consumption, the economy and the population.

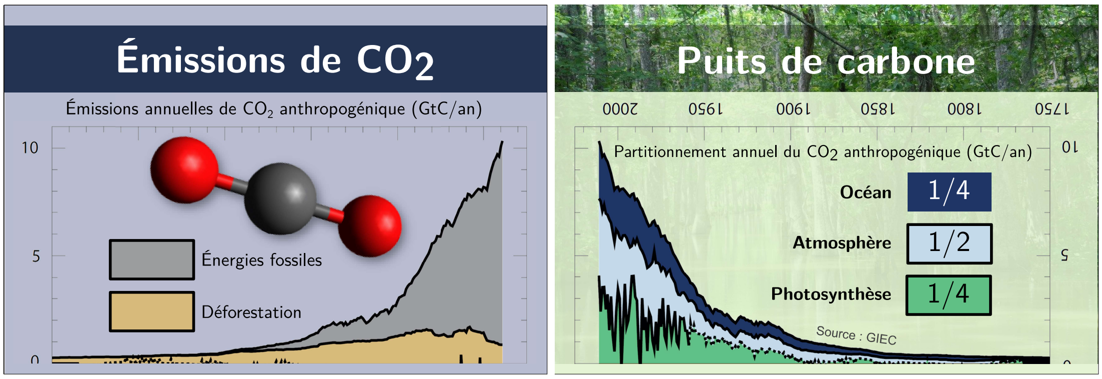


FIGURE 1 – *Carbon sources and sinks*

- CO_2 : emissions of CO_2 from energy (in tCO_2e/year)[4];
- E : annual energy consumption (in TWh/year, knowing that 1 GW of power corresponds to 8,76 TWh/year of energy. We recall that 1 Giga = 10^9 and 1 Tera =10^{12});
- GDP : annual gross domestic product (in$ ou €);
- POP : population (number of persons).

Figure 2 shows the historical trend and projections of the various factors in the Kaya identity on a global scale. Our objectives are to :

- link greenhouse gas emissions to energy consumption and efficiency energy consumption and efficiency, gross domestic product and population via the Kaya equation;
- calculate the order of magnitude of the various factors and their historical trends;
- discuss the possible evolution of the various factors and their compatibility with economic growth objectives, climate change, or simple common sense.

Avertissements

- The calculations below are a rough analysis, which essentially seeks to determine orders of magnitude to determine what is physically and historically possible and what is not.
- The various factors of the Kaya identity below are not independent, and do not lend themselves to a complete analysis of greenhouse gas emissions but focus solely on their energy-related dimension the use of fossil fuels. They do, however, provide a useful framework to discuss possible actions.
- Hence, we will consider here only greenhouse gas emissions generated by fossil fuels, which represent the vast majority, but not all, of human emissions. Combating climate disruption requires going beyond the scenarios below.

EN-ROADS survival guide

- Focus on temperature and climate impact (“ there’s more to life than CO_2 ”).
- The basis scenario only partially takes into account the commitments made by states at the COPs, as they are not meeting their commitments, see figure 3.
- The main levers on energy are financial, and therefore play indirectly on the production system.

4. By tCO_2e, we mean greenhouse gas emissions having an effect comparable to the emission of a ton of carbon dioxide : this unit allows to simplify by grouping the effect of different gases.

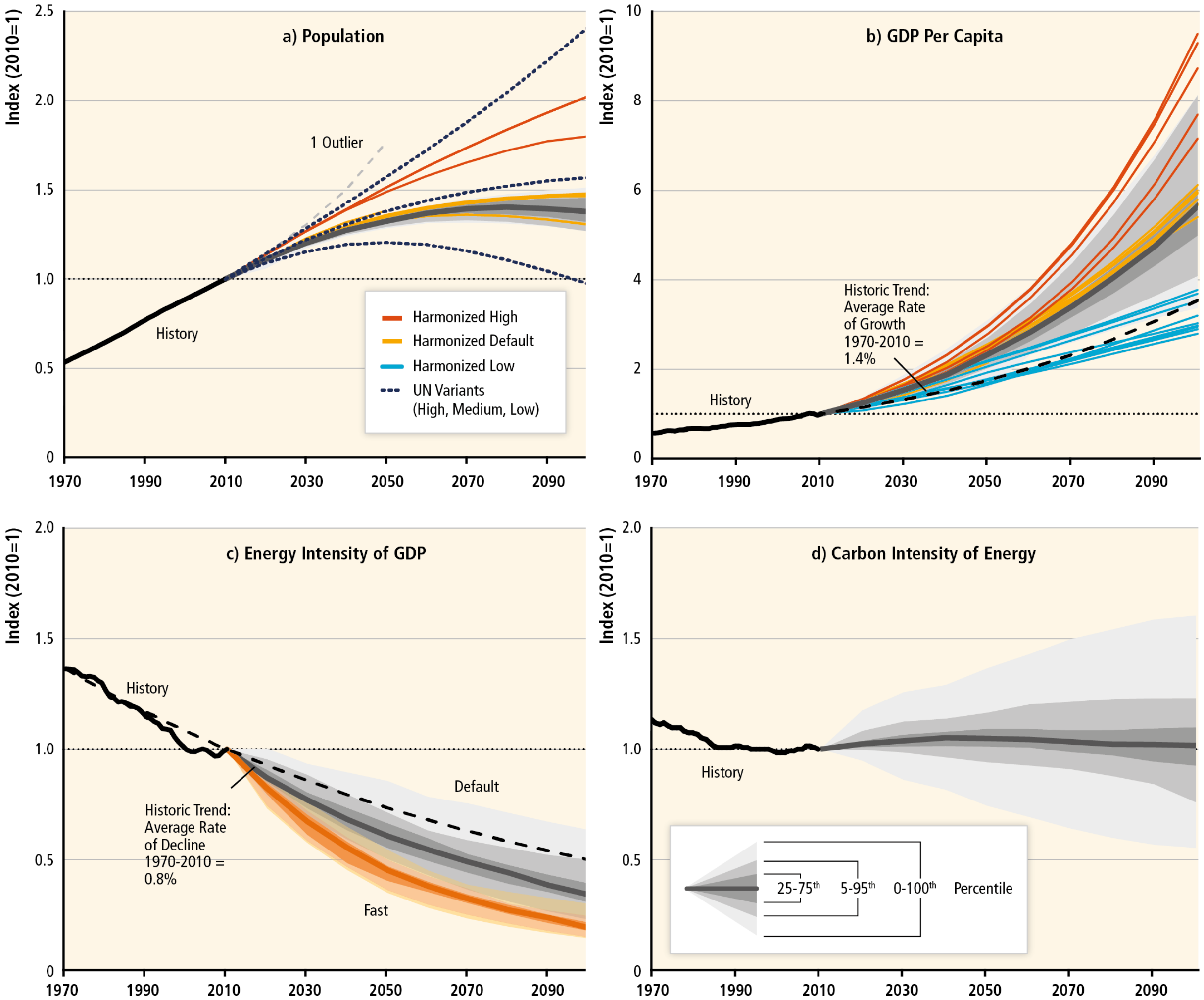


FIGURE 2 – *Historical trends and future projections for the factors of the Kaya identity (normalized to 2010 values), figure 6.1 by [2]. (a) Population. (b) GDP per capita (GDP/POP), aggregated at base-year exchange rate. (c) Energy intensity of GDP (E/GDP). (d) Energy carbonation (CO_2 /E), calculated on primary energy.*

- Directly influencing the production system requires the use of advanced levers, accessible via the ⋮ of each criterion.
- You can see the changes you've implemented via the menu : View/Actions and Outcome.
- A brief overview of the major CO_2 emission sectors in the world and in France in figure 4.

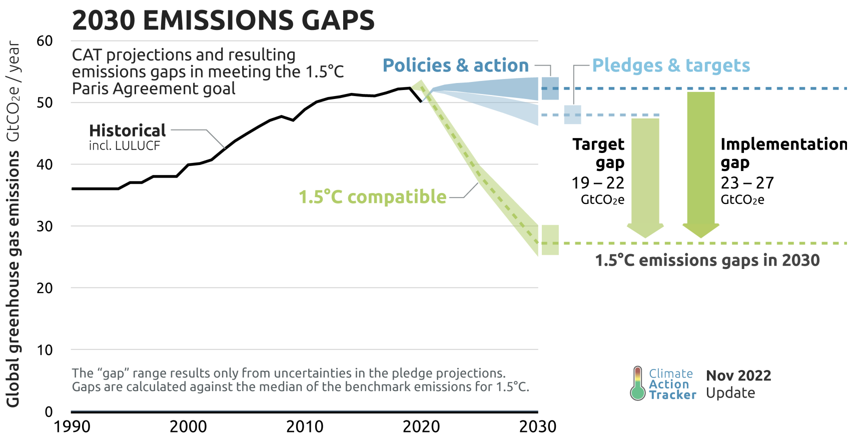


FIGURE 3 – https://climateactiontracker.org/media/images/CAT_2022-11_Graph_2030EmissionsGaps.original.png

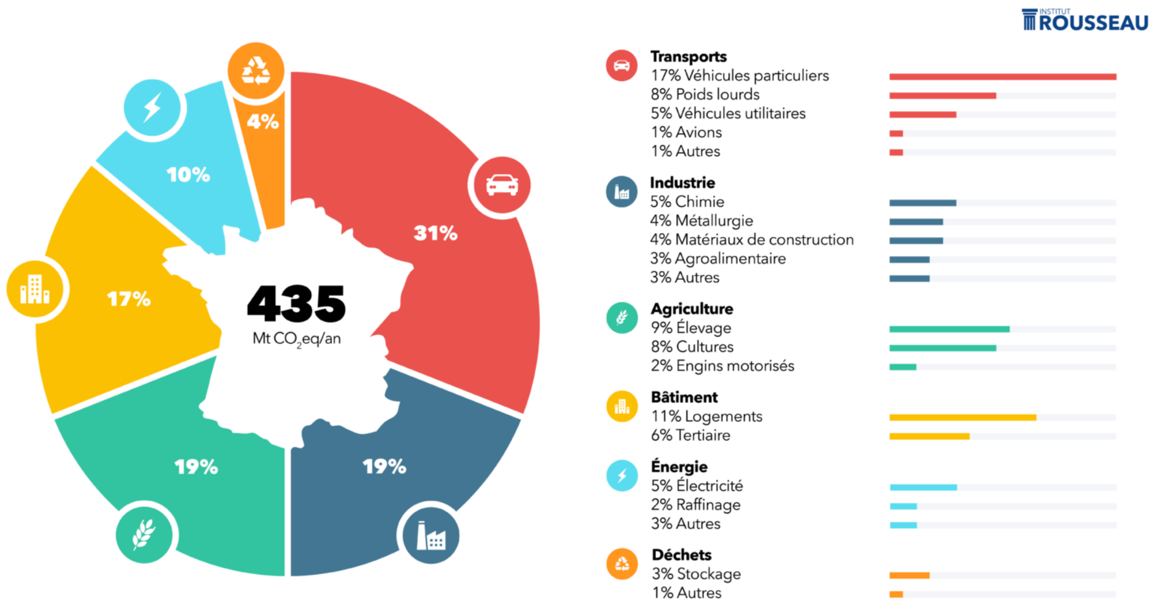


FIGURE 4 – *CO_2 emissions in France*

I Choice of the factors on which to act

Question 1 The factors (fractions) of the identity are named as follows :

- $\dfrac{CO_2}{E}$: carbon intensity of energy ;

https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-bior Rechercher

Fuels for heating and power

These represent figures for the carbon or carbon dioxide emitted by full combustion of each fuel, per unit of energy. Note that life cycle CO2 emissions depend strongly upon details of supply chains, production techniques, forestry or agricultural practice, transport distances, etc.

Fuel	Net CV	Carbon content	Approx. life cycle CO_2 emissions (see note 1)		Annual total CO_2 emissions to heat a typical house (20 MWh p.a.)		
	MJ/kg	%	kg/GJ	kg/MWh	kg	kg saved c.f. oil	kg saved c.f. gas
Hard coal	29	75	115	414	8,280	-2,000	-3,740
Oil	42	85	87	314	6,280	0	-1,740
Natural gas	38	75	63	227	4,540	1,740	0
LPG	46	82	72	259	5,180	1,100	-640
Electricity (UK grid - 2019)	-	-	71	256	5,120	1,160	-580
Electricity (large scale	-	-	16	58	1,160	5,120	3,380

FIGURE 5 – *Energy intensity of major fossil fuels.*

- $\frac{E}{PIB}$: energy intensity of the economy (economy reduced to it's GDP) ;
- $\frac{PIB}{POP}$: \$ or € per capita (wealth assimilated to GDP).

What are the factors on which technological improvements can play ? How would these factors then evolve ?

We note that despite significant progress in energy efficiency and clean energy, the reduction of emissions of CO_2 remains insufficient. To illustrate this point, we can play on the sliders of low-carbon energies (including new/hypothetical energies), " energy efficiency ", " electrification " and capture of CO_2 of En-ROADS. What is the overall impact on the level of warming ? Which levers have the most impact ?

Question 2 Interpret how the terms of the Kaya identity have evolved in recent human history from figure 2 and compare with the En-ROADS reference scenario (View/Kaya Graph).

Explain the improvement in the carbon intensity of energy in the 1970-1990 from figures 5 and 6.

Question 3 Would a drastic reduction in the population, for example by "removing" Indians, Africans and South Africans, Asians (excluding China), be a good solution for CO_2 emissions (beyond the small ethical problem that this poses). Reason from Figure 7.

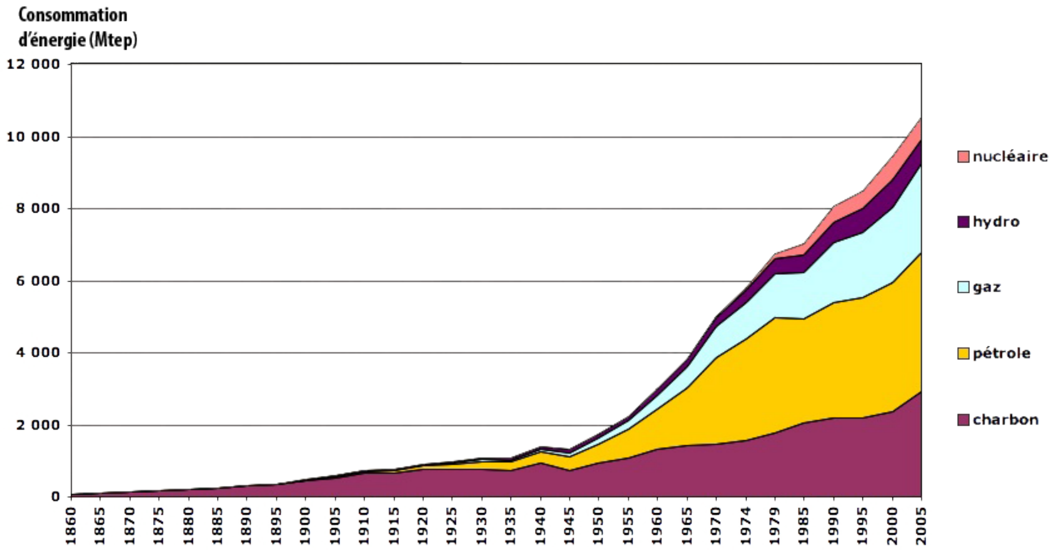


FIGURE 6 – *Produced energy by source in the world.*
Source : https://jancovici.com/transition-energetique/l-energie-et-nous/a-quoi-ressemble-notre-consommation-energetique-actuellement/

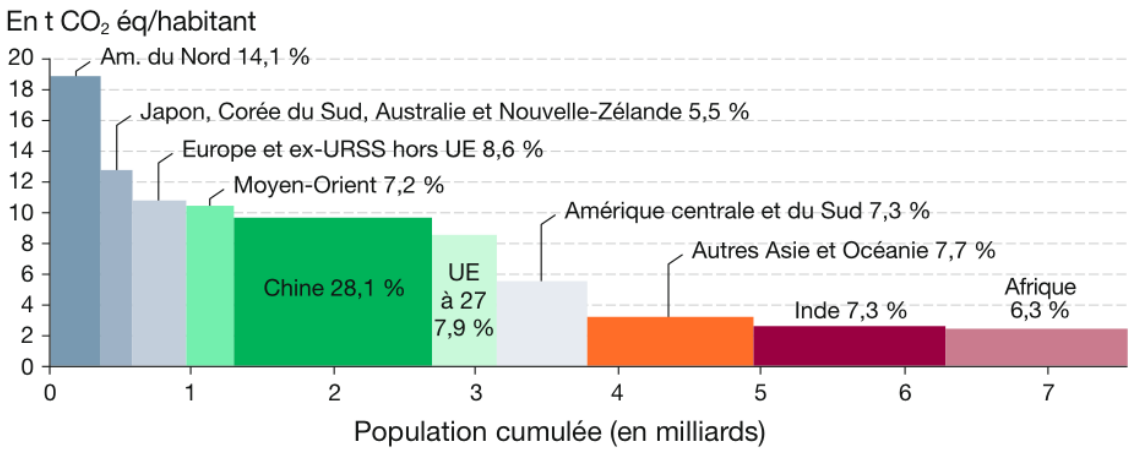
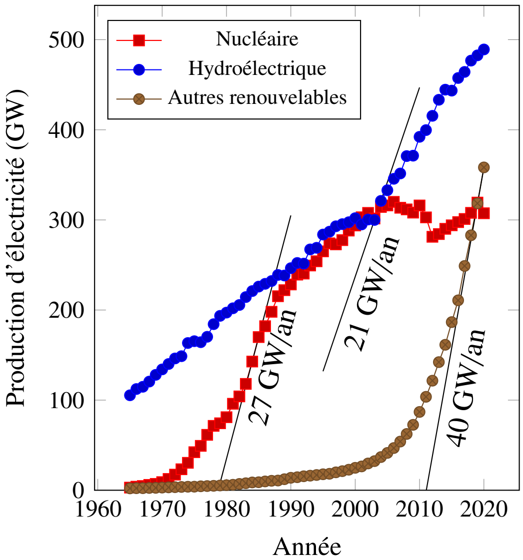


FIGURE 7 – *Territorial GHG emissions by country according to number of inhabitants. The area of the rectangle is total consumption. Source : Service des statistiques du ministère de la transition écologique.*

Uranium : conventional reserves	7,1 [5] – 27 [6]	(10^9 kg)
Electricity production (conventional reactor)	$2 \cdot 10^{11}$	(J/kg of uranium)

Table 1 – *World uranium reserves and electrical energy per kg of uranium for conventional reactors.*

II Energy decarbonization (factor CO2 / E)



Filière	**gCO_2e/ kWh** (sur le cycle de vie)		
	ADEME (France)	**ADEME (Monde)**	**GIEC**
Charbon	1058	960–1050	710–950
Pétrole	730	778	N/A
Gaz	418	443	410–650
Nucléaire	6	66	4–110
Hydroélectrique	10–13		3–2000
Photovoltaïque	44	32	18–180
Éolien	14–16	9–10	7–56

Figure 8 – *Left : history of global electrical power generation via “ decarbonated ” sources : renewables and nuclear power [3]. (We're talking about production, not production capacity, which allows us to include the effective load factor directly ; i.e. we look at the power actually produced by intermittent generation resources, not their maximum output). Right : GHG emissions per kWh of electricity produced for different types of power generation [4, 5]. (The carbon footprint of photovoltaic and hydroelectric power are highly variable geographically, depending on sunshine levels and other local conditions. The carbon footprints of photovoltaic and are also highly variable, depending on the country's electricity production mix of the country where the solar panels are manufactured and where the uranium is enriched).*

Question 4 Assuming that all energy uses can be converted to electricity to electricity, using decarbonized technologies (see figure 8), How much power do we need to deploy each year to decarbonize current global consumption (whose order of magnitude [5] is 10 TW) over a 50-year period ? Compare with the historical trend given figure 8.

Question 5 From the data in table 1, estimate how many years the world's current energy needs, given that 1 Joule = 2.78×10^{-7} kWh. Comment. Using the En-ROADS simulator, what gain in energy decarbonization can be achieved by subsidizing nuclear power ? What effect does this have on global temperature ?

5. Global energy consumption was estimated at 18.4 TW on average in 2019, of which 84 % via fossil fuels [3]. Europe accounts for 2.6 TW (73 % fossil fuels). These figures are an aggregation of the thermal energy for fossil fuels, and thermal energy equivalents for other energy sources. Converting this consumption to to decarbonized electricity means taking into account higher efficiencies conversion factor, and so on. For simplicity's sake, we'll just take an order of magnitude of 10 TW.

	France	Europe (UE)	World
PIB total ($)	$2{,}7 \cdot 10^{12}$	$15{,}6 \cdot 10^{12}$	$87{,}6 \cdot 10^{12}$
POP (millions)	67	447	7714
GDP/POP ($/person)	42000	35000	11000
(adjusted for purchasing power parity)	49000	46000	18000

TABLE 2 – *GDP : total and per person in 2019. [7, 8]*

III GDP energy intensity (factor E/GDP)

Question 6 Based on figure 2(c), what order of magnitude reduction can we reasonably expect for E/GDP in 2060 ? Compare with the En-ROADS reference scenario, which shows a factor of E/GDP = 1.86 ExaJoules/Trillion $ in 2060, i.e. a factor of 0.5 compared to 2010 (division by 2).

IV GDP per person (factor PIB / POP)

Question 7 With the factors calculated above :

- POP : increase by a factor of 1.5 ;
- E/PIB : division by 2 or 3, say 3 if we're optimistic ;
- CO_2 /E : we're missing at least a factor of 2 or 3 on the speed of decarbonized power plants, so at best we can hope to to replace half of the existing plants, let's say a division by 2.

What is the reduction factor of GDP/POP if we want to reduce CO_2 to 10 % of its current value in 50 years ? Playing with the En-ROADS growth slider, what factor can we hope to gain in 50 years ?

Références

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