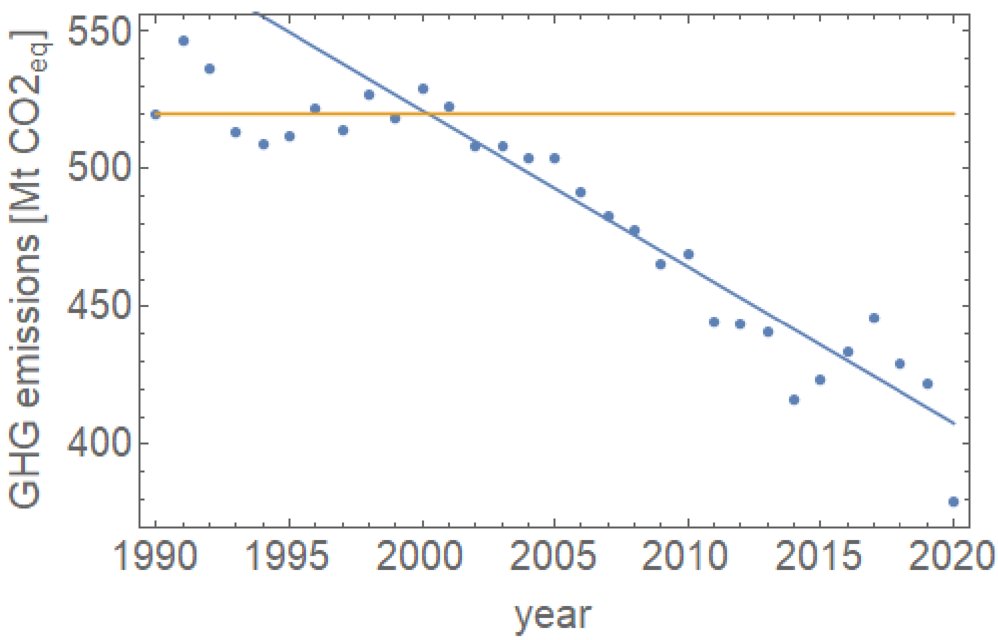
PHY 555 - Homework 2022
LMDI analysis of France National Emissions

This homework is largely based on a recently published study[1] by the entitled "Les facteurs d'évolution des émissions de CO2 liées à l'énergie en France de 1990 à 2019". You will see that the discussions and methods (LMDI decomposition, contribution of nuclear and renewables...) are really used in public institutions ! You will also find further analysis on other sectors (buildings, transport...) not addressed in this assignment.

1. The point of this question was to have you handle a table with 100000+ lines, which requires filtering out data. This can be done with you favorite spreasheet application, or python code. The raw data could be found at

   eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-18

   Selecting France as the only country, "all greenhouse gases" as pollutant and "Total net emissions (UNFCCC)" as sector, we get

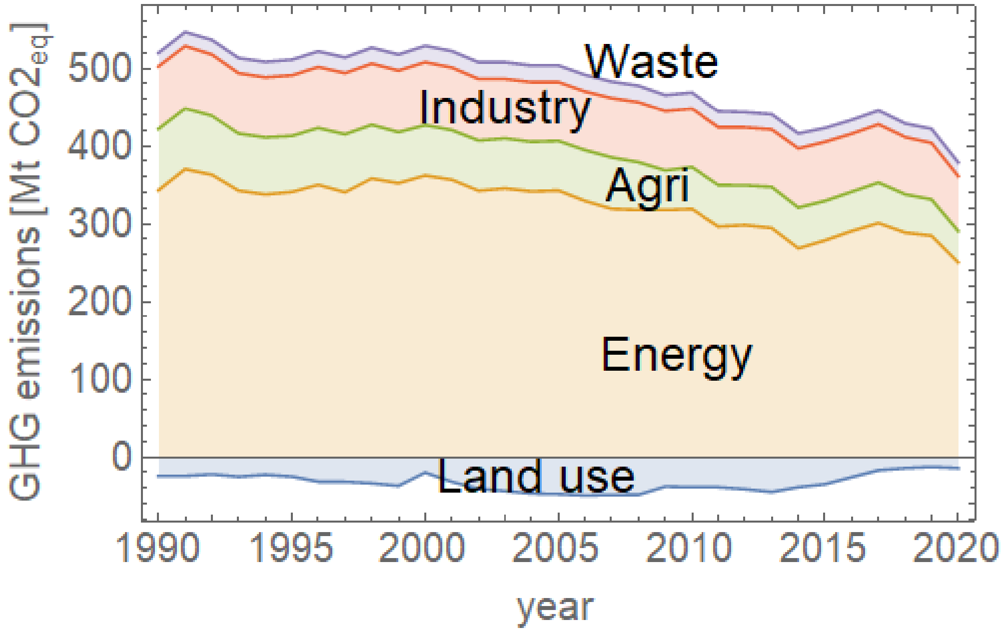
   Net emissions have significantly decreased over the period, roughly by -20% over 30 years. Emissions are relatively stable for the first ten years, then decrease by $\sim 1.5\%$/year. The last point is significantly below the global behaviour, essentially due to covid impacts.

   It is important to realize that the quantity estimated here are emissions on the national territory - not the footprint, which deducts emissions of manufactured goods exported outside the country, and adds emissions induced by goods imported to the country. Both perimeters have their relevance, but it is critical to keep in mind which one is being considered.

2. The United Nations Framework Convention on Climate Change follows the IPCC guidelines for national GHG inventories. Filtering the data by sector, we can decompose the total net emission into the 5 usual

[1] https://www.statistiques.developpement-durable.gouv.fr/les-facteurs-devolution-des-emissions-de-co2-liees-lenergie-en-france-de-1990-2019

sectors. We find that the energy sector (ie the emissions induced by the direct combustion of fuels for any application) accounts for 70% of the national emissions. Focusing on energy emissions only also reduces GHG emissions to essentially CO2, as other GHG (CH4, NO2...) originate mostly from the other sectors.



3. The point of this question is to start clarifying what causes the emission to decrease.

   (a) Kaya equation is a tautology, which simply requires to turn correctly the concepts into numbers.

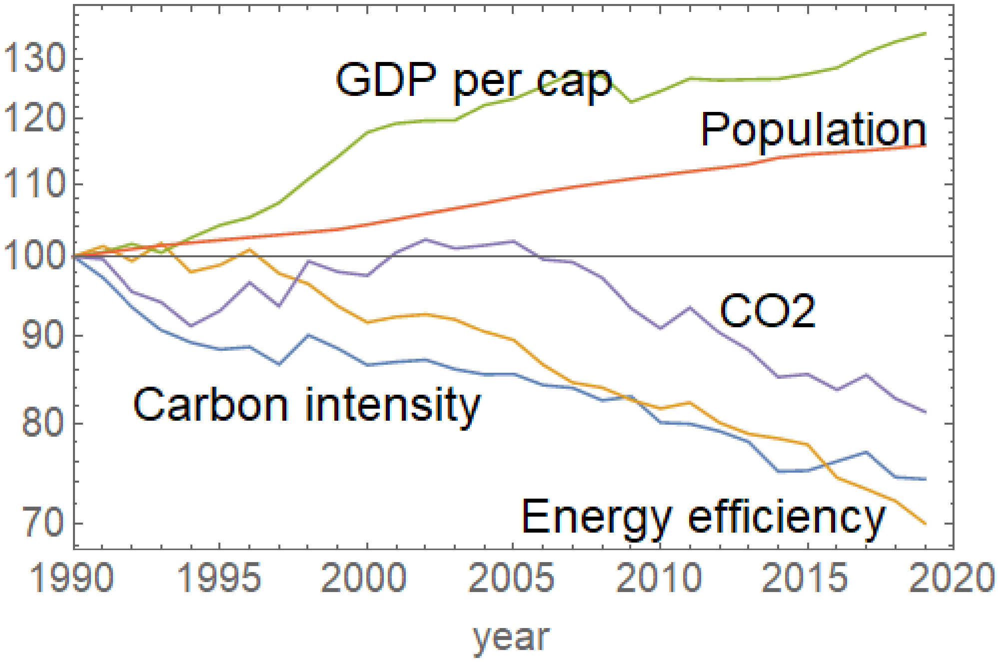
      i. The carbon intensity of the energy mix is the ratio between CO2 emissions from energy and primary energy supply (how much CO2 is emitted to create 1 energy unit)

      ii. The energy intensity of the economy is the ratio between the primary energy supply and the GDP (how much energy is needed to create 1 GDP unit)

      iii. The GDP per capita is the ratio between GDP and capita (no kidding), leading to

$$CO_2 = \frac{CO_2}{\text{Energy}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{GDP}}{\text{Population}} \times \text{Population}$$

   (b) A log scale turns a product into a sum - so the result (in this case, CO2 emissions) is visually obtained by adding the different contributions : the distance of the purple line (CO2 emissions) to the reference value is the sum of the distances of all the other lines.



(c) The Kaya analysis suggests that the observed diminution in GHG emissions is mostly due to the improvement of energy intensity of the economy and to the decrease of the carbon intensity of the energy mix, which managed to over compensate the increase in population and in GPD per capita.
In more details,

- the GDP per capita increases much faster than the population ; population growth is quite steady, while GDP per capita increases rapidly from 1993 to 2000, then more slowly. During the period with the fast increase of the GDP per capita, the other factors are not sufficient to bring emissions down. Emissions decrease more significantly when the GDP per capita dynamics becomes slow enough for the other factors to take over.
- Carbon and energy intensity have similar contributions, but with a different timing. The energy intensity of the economy remained constant for 5-6 years before decreasing at a fixed pace, while the carbon intensity first had a steep decline, followed by a slower evolution.

Another line of analysis could be to compare the values and trends to neighbouring countries, to Europe, to OECD or to the rest of the world.

4. We first focus on the reduction of the carbon intensity of the energy mix, and try to understand what is behind the observed behavior.

(a) CO2 emissions for energy production are due to the combustion of fossil fuels. To reduce the carbon intensity, we can either increase the reduce the amount of CO2 emitted when burning fuels (either by increasing the efficiency of plants so that the same combustion produces more energy, by switching coal to gas, or by capturing CO2 molecules to avoid emissions in the atmosphere), or produce energy without burning fuels at all - which means either nuclear, or renewables.

(b) This is again a tautology. Considering $E_{\text{Total}} = E_{\text{Fossil}} + E_{RE} + E_{\text{nuc}}$.

$$\begin{aligned} \frac{\mathrm{CO_2}}{\mathrm{E_{Total}}} &= \frac{\mathrm{CO_2}}{\mathrm{E_{Fossil}}} \times \frac{E_{\text{Fossil}} + E_{\text{nuc}}}{E_{\text{Total}}} \times \frac{E_{\text{Fossil}}}{E_{\text{Fossil}} + E_{\text{nuc}}} \\ &= \frac{\mathrm{CO_2}}{\mathrm{E_{Fossil}}} \times \frac{E_{\text{Total}} - E_{\text{RE}}}{E_{\text{Total}}} \times \frac{E_{\text{Fossil}}}{E_{\text{Fossil}} + E_{\text{nuc}}} \\ &= \frac{\mathrm{CO_2}}{\mathrm{E_{Fossil}}} \times \underbrace{(1 - r_{\text{RE}})}_{\text{contribution RE}} \times \underbrace{\frac{r_{\text{fossil}}}{r_{\text{fossil}} + r_{\text{nuc}}}}_{\text{contribution nuclear}} \end{aligned} \tag{1}$$

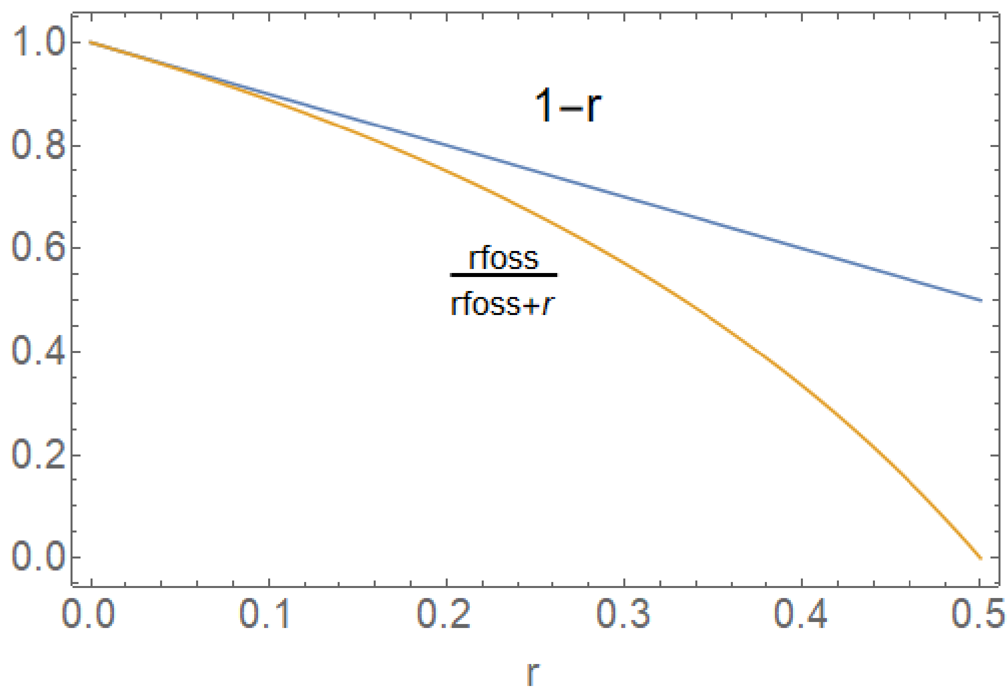
and a similar trick with $(E_{\text{Fossil}} + E_{RE})$ instead of $(E_{\text{Fossil}} + E_{\text{nuc}})$ leads to the other expression

$$\frac{\mathrm{CO_2}}{\mathrm{E_{Total}}} = \frac{\mathrm{CO_2}}{\mathrm{E_{Fossil}}} \times \underbrace{\frac{r_{\text{fossil}}}{r_{\text{fossil}} + r_{\text{RE}}}}_{\text{contribution RE}} \times \underbrace{(1 - r_{\text{nuc}})}_{\text{contribution nuclear}} \tag{2}$$

(c) The main point of this question is to realize that the way to quantify the contributions of the different effects relies on arbitrary choices and can bias the numerical results. While both *global* expressions are obviously the same (both are equal toCO_2/E_{Total} by definition) ; by contrast, they lead to different ways to quantify the contribution of renewable and nuclear energies.

To realize this, consider a mix with equal share r of renewables and nuclear, and $1-2r$ of fossil. We expect a priori that "the contribution of nuclear" and "the contribution of renewable" should have the same value, since their shares and emissions are the same. Let's check this. According to the first expression, the contribution of renewable is $(1-r)$ and that of nuclear is $\frac{(1-2r)}{(1-2r)+r}$. When the mix is essentially fossil (ie $r \ll 1$), then $\frac{(1-2r)}{(1-2r)+r} \simeq (1-2r)\times(1+r) \simeq 1-r$ and both expresions are indeed identical. By contrast, if the mix is essentially carbon free (ie $CO_2/E = 0$) with half nuclear, half renewable ($r \to 1/2$), then the "contribution of renewable" is $1-r = 1/2$ while the "contribution of nuclear" is $\frac{(1-2r)}{(1-2r)+r} = 0$ - so it seems the mix is carbon neutral just thanks to the nuclear production.

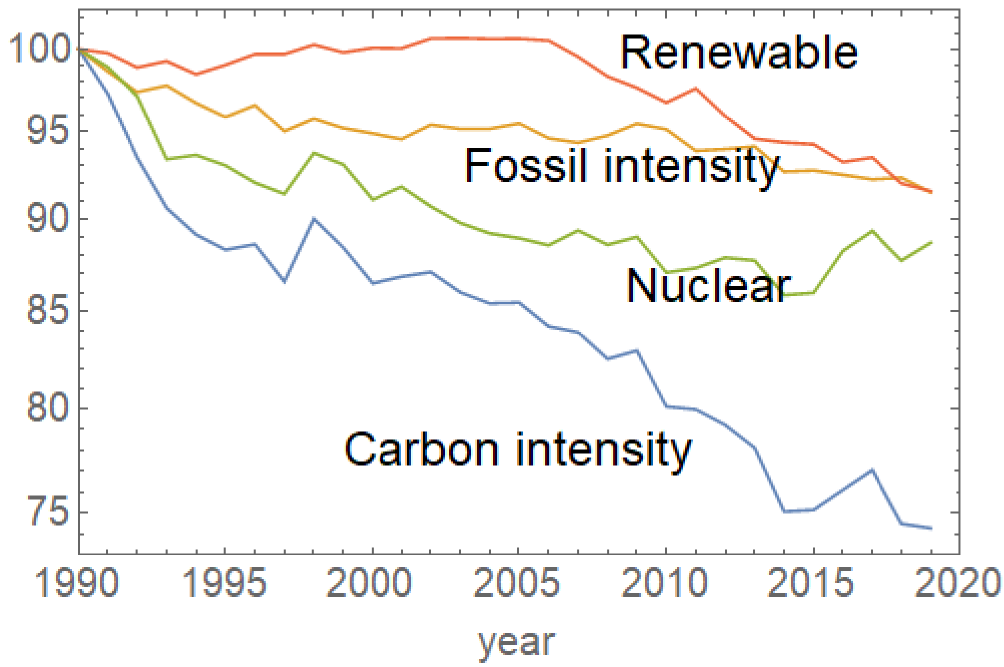
The first decomposition eq(1) is thus biased in favor of the nuclear, while the second eq(2) is biased in favour of renewables.



(a) Mixing both solutions to treat renewable and nuclear in a symmetric way:

$$\frac{CO_2}{E_{Total}} = \frac{CO_2}{E_{Fossil}} \times \underbrace{\sqrt{(1-r_{RE})\frac{r_{fossil}}{r_{fossil}+r_{RE}}}}_{\text{contribution RE}} \times \underbrace{\sqrt{(1-r_{nuc})\frac{r_{fossil}}{r_{fossil}+r_{nuc}}}}_{\text{contribution nuclear}} \tag{3}$$

(b) Leading to the following result - there again, the adding the three contributions



Carbon intensity as signicantly decreased over the period by about 25%, in a quite steady way. Over the period, the largest contribution to the decrease of emission is the increasing share of nuclear (the green line is below the other lines on the figure). Since 2005 however, the contribution of nuclear production remains approximately constant (or even decreases in the last few years), and the reduction in carbon intensity appears to be mostly due to the increase of renewable production - which was very small until then. This contribution remains smaller than that of improving the carbon content of fossil energies, but the ratio is just about to change, and the dynamics is favorable.

5. To gain some understanding on the energy intensity of the economy, we focus on the productive sector and instead of considering (as in Kaya) the total GDP and the total primary energy supply, we will the revenue and energy consumption of each productive subsector (industry, agriculture and tertiary).

$$\mathrm{CO}_2(n) = \sum_i \underbrace{A(n) \times \overbrace{\frac{A_i(n)}{A(n)}}^{S_i(n)} \times \overbrace{\frac{E_i(n)}{A_i(n)}}^{I_i(n)} \times \overbrace{\frac{CO_2^i(n)}{E_i(n)}}^{C_i(n)}}_{CO_2^i(n)}$$

(a) Writing the emissions as suggested highlights four factors

- $A(n)$ is the global activity of the productive sector during year n (estimated as the total revenue) $\rightarrow$ CO2 emissions will change if the national production changes, quite obviously
- $S_i(n)$ is the share of subsector i in the global activity during year n (ie the revenue of the subsector divided by the total revenue) $\rightarrow$ At fixed global activity, CO2 emissions will change if the activity moves from a highly emitting sector to a less emitting sector, or vice versa. This is called a structural effect.
- $I_i(n)$ is the energy intensity of the subsector i (ie the energy consumption of the sector divided by the revenue of the subsector) $\rightarrow$ If we use less energy to produce the same revenue, we burn less fuels and emit less CO2.
- $C_i(n)$ is the carbon intensity of the energy used by the subsector (estimated as the energy related emissions of the sector divided by the energy consumption) $\rightarrow$ If we emit less CO2 to produce the same energy, we obviously reduce emissions.

(b) The LMDI is standard in the energy sector

i. Basic calculus using the provided definitions

$$
\begin{aligned}
&D_{Act}(n)D_{Str}(n)D_{Int}(n)D_{Carb}(n)\\
&= \exp\left(\sum_i \left[w_i(n)\left(\log\frac{A(n)S_i(n)I_i(n)C_i(n)}{A(\text{ref})S_i(\text{ref})I_i(\text{ref})C_i(\text{ref})}\right)\right]\right)\\
&= \exp\left(\sum_i \left[w_i(n)\log\frac{CO_2^{(i)}(n)}{CO_2^{(i)}(\text{ref})}\right]\right)\\
&= \exp\left(\sum_i \left[\left(\frac{CO_2^{(i)}(n)-CO_2^{(i)}(\text{ref})}{CO_2(n)-CO_2(\text{ref})}\frac{\log\left(\frac{CO_2(n)}{CO_2(\text{ref})}\right)}{\log\frac{CO_2^{(i)}(n)}{CO_2^{(i)}(\text{ref})}}\right)\log\frac{CO_2^{(i)}(n)}{CO_2^{(i)}(\text{ref})}\right]\right)\\
&= \exp\left(\log\left(\frac{CO_2(n)}{CO_2(\text{ref})}\right)\frac{\sum_i\left(CO_2^{(i)}(n)-CO_2^{(i)}(\text{ref})\right)}{CO_2(n)-CO_2(\text{ref})}\right)\\
&= \exp\left(\log\left(\frac{CO_2(n)}{CO_2(\text{ref})}\right)\right) = \frac{CO_2(n)}{CO_2(\text{ref})}
\end{aligned}
$$

ii. Let's assume $\forall i,\ C_i(n) = rC_i(\text{ref})$, and all other parameters remain constant. This leads to $\text{CO}_2^{(\text{i})}(n) = r\text{CO}_2^{(\text{i})}(\text{ref})$ and $\text{CO}_2(n) = r\text{CO}_2(\text{ref})$. What we expect is that all factors should be 1 (no change), except the factor corresponding to the carbon intensity D_{carb} which should be r. In the LMDI analysis

$$
\begin{aligned}
\frac{A(n)}{A(\text{ref})} &= 1 \Rightarrow D_{Act}(n) = 1\\
\forall i\ \frac{S_i(n)}{S_i(\text{ref})} &= 1 \Rightarrow D_{Str}(n) = 1\\
\forall i\ \frac{I_i(n)}{I_i(\text{ref})} &= 1 \Rightarrow D_{Int}(n) = 1\\
D_{Carb}(n) &= \exp\left(\sum_i [w_i(n)(\log r)]\right)\\
&= \exp\left(\sum_i\left[\frac{(r-1)\,CO_2^{(i)}(\text{ref})}{(r-1)\,CO_2(\text{ref})}\frac{\log r}{\log r}(\log r)\right]\right)\\
&= \exp\left(\log r\frac{\sum_i CO_2^{(i)}(\text{ref})}{CO_2(\text{ref})}\right) = \exp(\log r) = r
\end{aligned}
$$

So the analysis attributes indeed the intensity reduction to the D_{carb} factor only, with the expected value. The same analysis can be applied to a global change of energy efficiency as well.

iii. Let's assume $C_k(n) = rC_k(\text{ref})$, and all other parameters remain constant. This leads to $\text{CO}_2^{(\text{k})}(n) = r\text{CO}_2^{(\text{k})}(\text{ref})$, $\text{CO}_2^{(\text{i}\neq\text{k})}(n) = \text{CO}_2^{(\text{i}\neq\text{k})}(\text{ref})$ and $\text{CO}_2(n) - \text{CO}_2(\text{ref}) = \text{CO}_2^{(\text{k})}(n) - \text{CO}_2^{(\text{k})}(\text{ref})$. We expect all factors should be 1 (no change), except the factor corresponding to the carbon intensity D_{carb}. The exact value is cannot be directly related to r (if we reduce the carbon intensity of a sector with a major or a minor contribution, we will get very diffrent impacts on the global CO2 emissions). In the LMDI analysis

$$\frac{A(n)}{A(\text{ref})} = 1 \Rightarrow D_{Act}(n) = 1$$

$$\forall i \; \frac{S_i(n)}{S_i(\text{ref})} = 1 \Rightarrow D_{Str}(n) = 1$$

$$\forall i \; \frac{I_i(n)}{I_i(\text{ref})} = 1 \Rightarrow D_{Int}(n) = 1$$

$$\begin{aligned} D_{Carb}(n) &= \exp\left(\sum_{i \neq k} [w_i(n)\,(\log 1)] + w_k(n) \log r\right) \\ &= \exp\left(\frac{\log\left(\frac{CO_2(n)}{CO_2(\text{ref})}\right)}{\log r}\,(\log r)\right) \\ &= \frac{\mathrm{CO_2(n)}}{\mathrm{CO_2(ref)}} \end{aligned}$$

And a similar calculation can be made when changing the energy intensity rather than the carbon intensity.

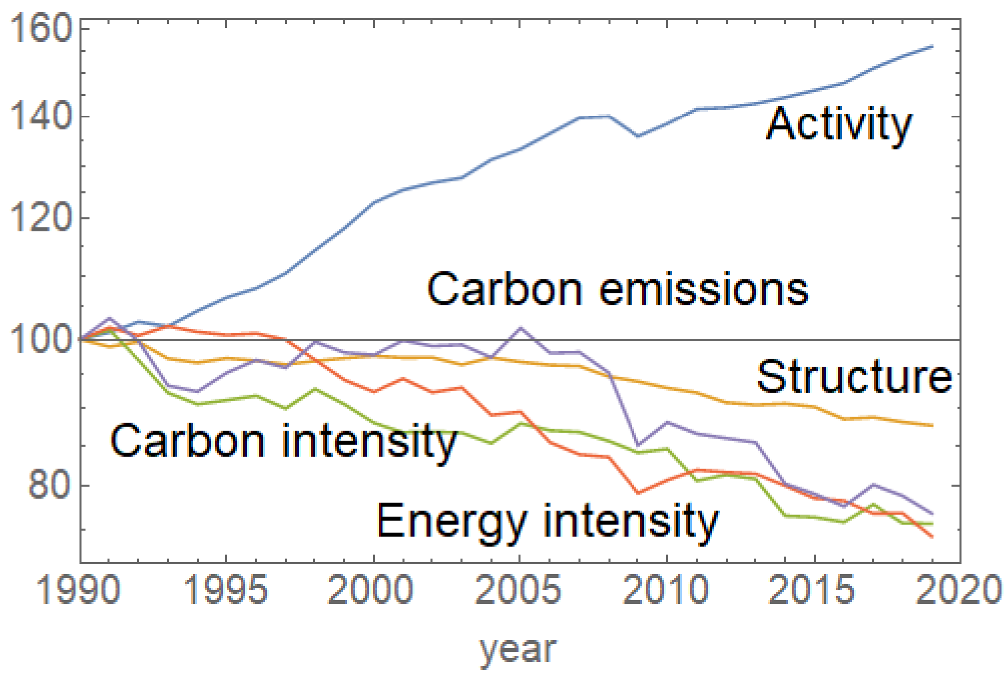
(c) Ploting in the same way as before. The LMDI analysis gives a estimation for the influence of energy intensity at

$$D_{Int}(2019) = 0.74$$

By contrast, a simple ratio overestimates the impact of the energy intensity

$$\frac{E_{\text{Total}}(2019)}{A_{\text{Total}}(2019)} \times \frac{1}{\frac{E_{\text{Total}}(1990)}{A_{\text{Total}}(1990)}} = 0.66$$

The difference comes essentially from the fact that the simple ration includes (without caution) a structural evolution : the share of tertiary activities has increased from 73% to 78.5%, and this subsector uses much less energy per GDP than industrial productions, and uses mostly low carbon electricity - so increasing this share decreases the emissions.



6. Carbon emissions have decreased by 1/3 over the period, even if the global activity increases by more than 50%. Most of this decrease has occured after 2005. The main drivers are the improvements in carbon and energy intensities - in equal amounts. An abrupt decrease can be observed in 2008 in both carbon emissions and the global activity, due to the financial crisis. The structural shift towards the tertiary sector (de industrialization) has contributed for about 12% to the reduction.