

CO₂ emissions and economic development: at the border of physics, economy and sustainability

José-Enrique García-Ramos

¹Departamento de Ciencias Integradas, Universidad de Huelva, Spain

²Centro de Estudios Avanzados en Física, Matemática y Computación, Universidad de Huelva, Spain



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Summary

- Motivation
- Why economy is so important: the Kaya identity
- How to understand the past emissions:
 - The Logarithmic-Mean Divisia index: application to the European Union
 - The Granger-causality analysis: application to the six world larger CO₂ emitters
- A simple model to forecast future CO₂ emissions: application to Venezuela
- Conclusions

Motivation

Global warming: a reality

Global Land and Ocean Temperature Anomalies

Change in global surface temperature relative to 1910-2000 average temperatures

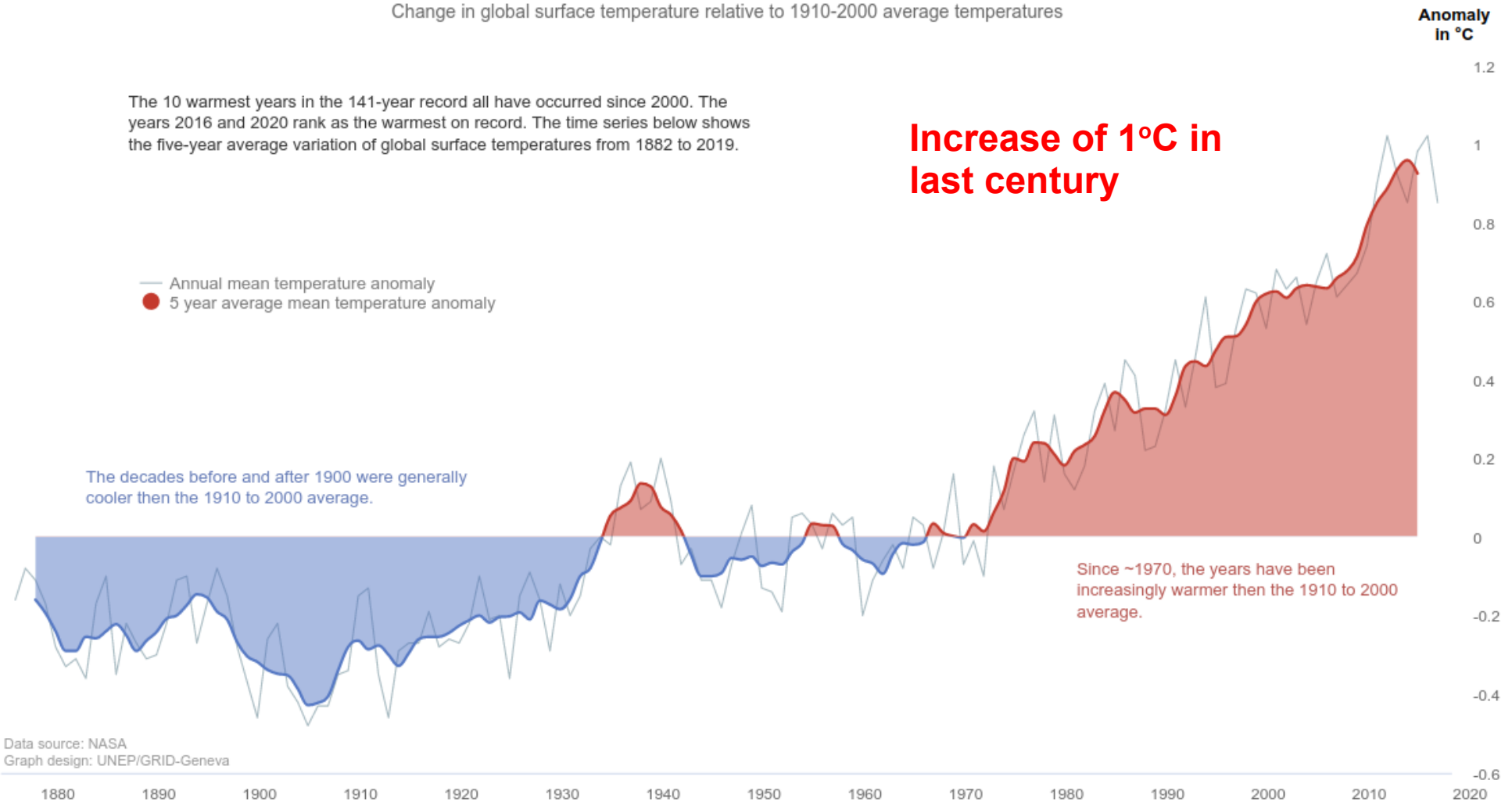
The 10 warmest years in the 141-year record all have occurred since 2000. The years 2016 and 2020 rank as the warmest on record. The time series below shows the five-year average variation of global surface temperatures from 1882 to 2019.

Increase of 1°C in last century

— Annual mean temperature anomaly
 ● 5 year average mean temperature anomaly

The decades before and after 1900 were generally cooler than the 1910 to 2000 average.

Since ~1970, the years have been increasingly warmer than the 1910 to 2000 average.

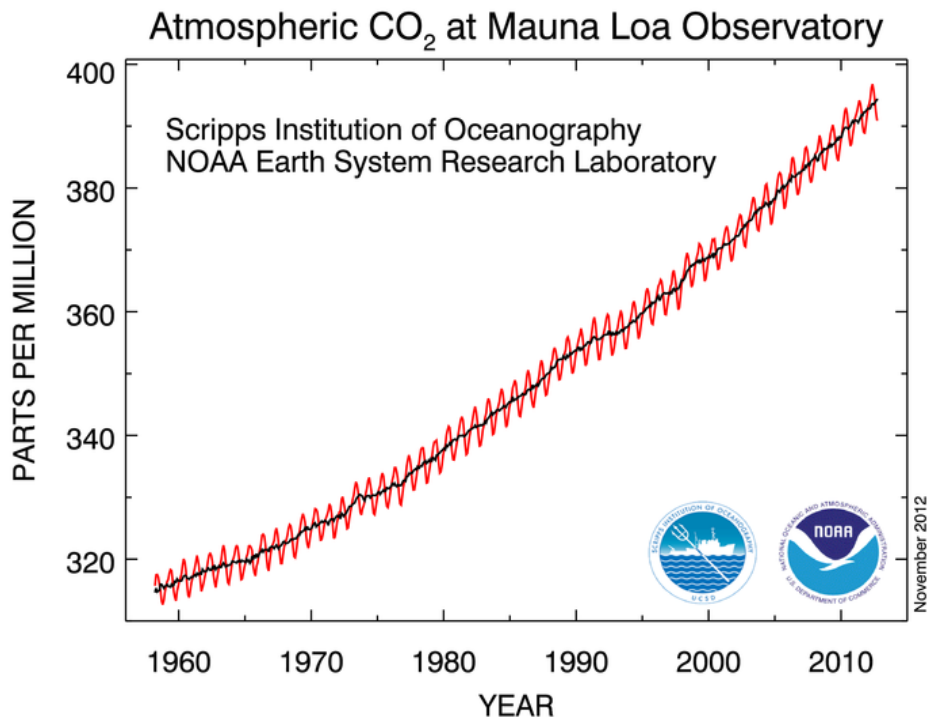


Data source: NASA
 Graph design: UNEP/GRID-Geneva

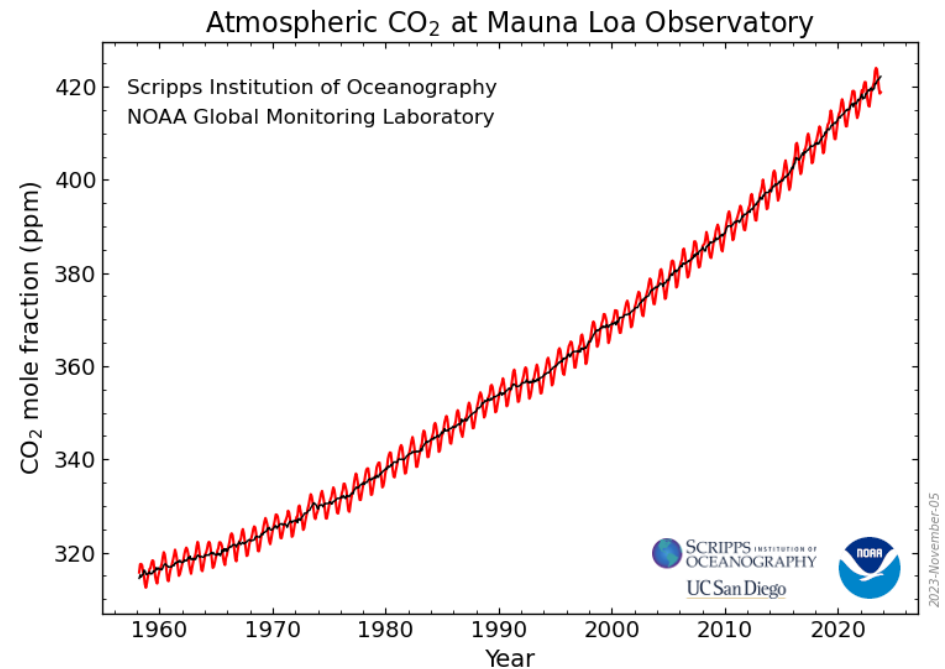
https://graphs.unepgrid.ch/graph_global_temperatures_2.php

Global warming: a reality

In 1958 Roger Revelle from Scripps Institution of Oceanography understood the importance of taking a global and continuum record of CO₂ concentrations



October 2012: 391.01 ppm
 October 2011: 388.92 ppm

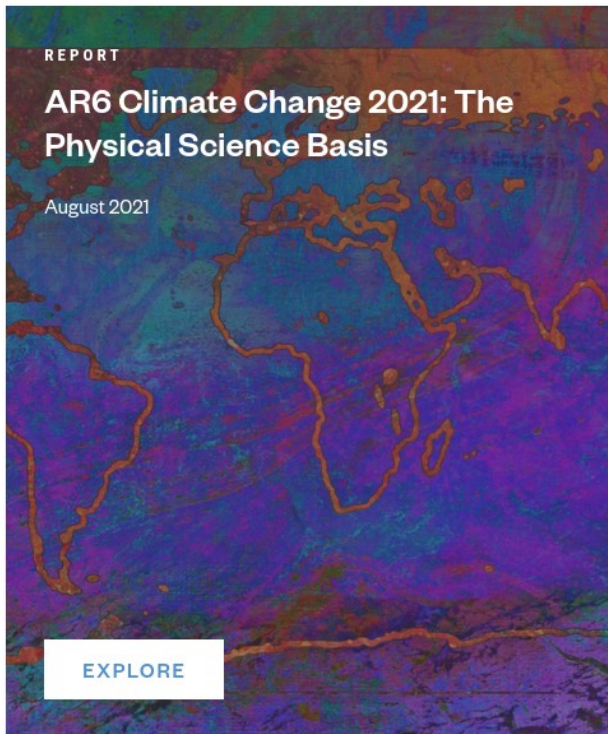


October 2023: 418.82 ppm
 October 2022: 415.74 ppm

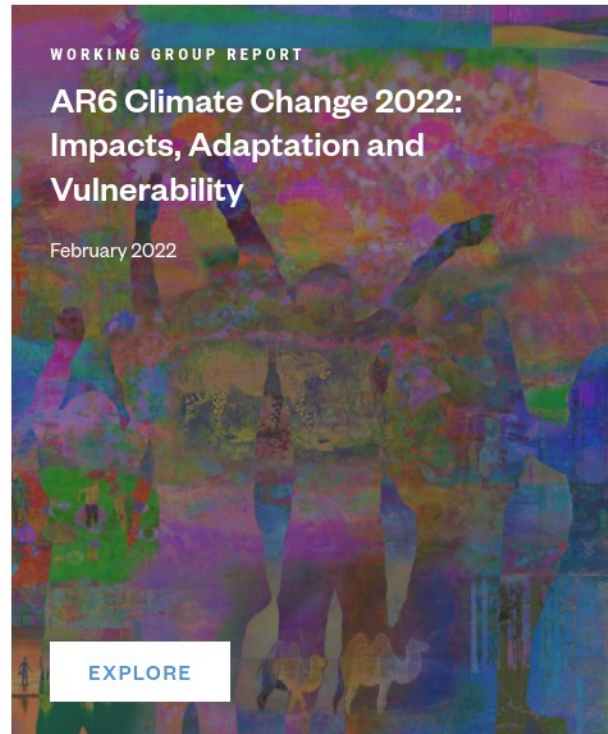
Last updated: Nov 05, 2023

Beyond physics

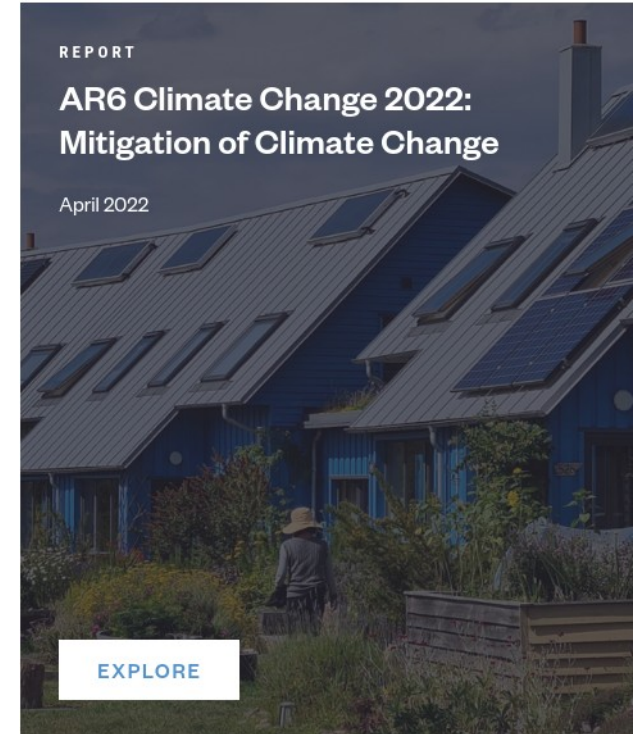
The Intergovernmental Panel on Climate Change (IPCC) The six assessment report (AR6)



2391 pages

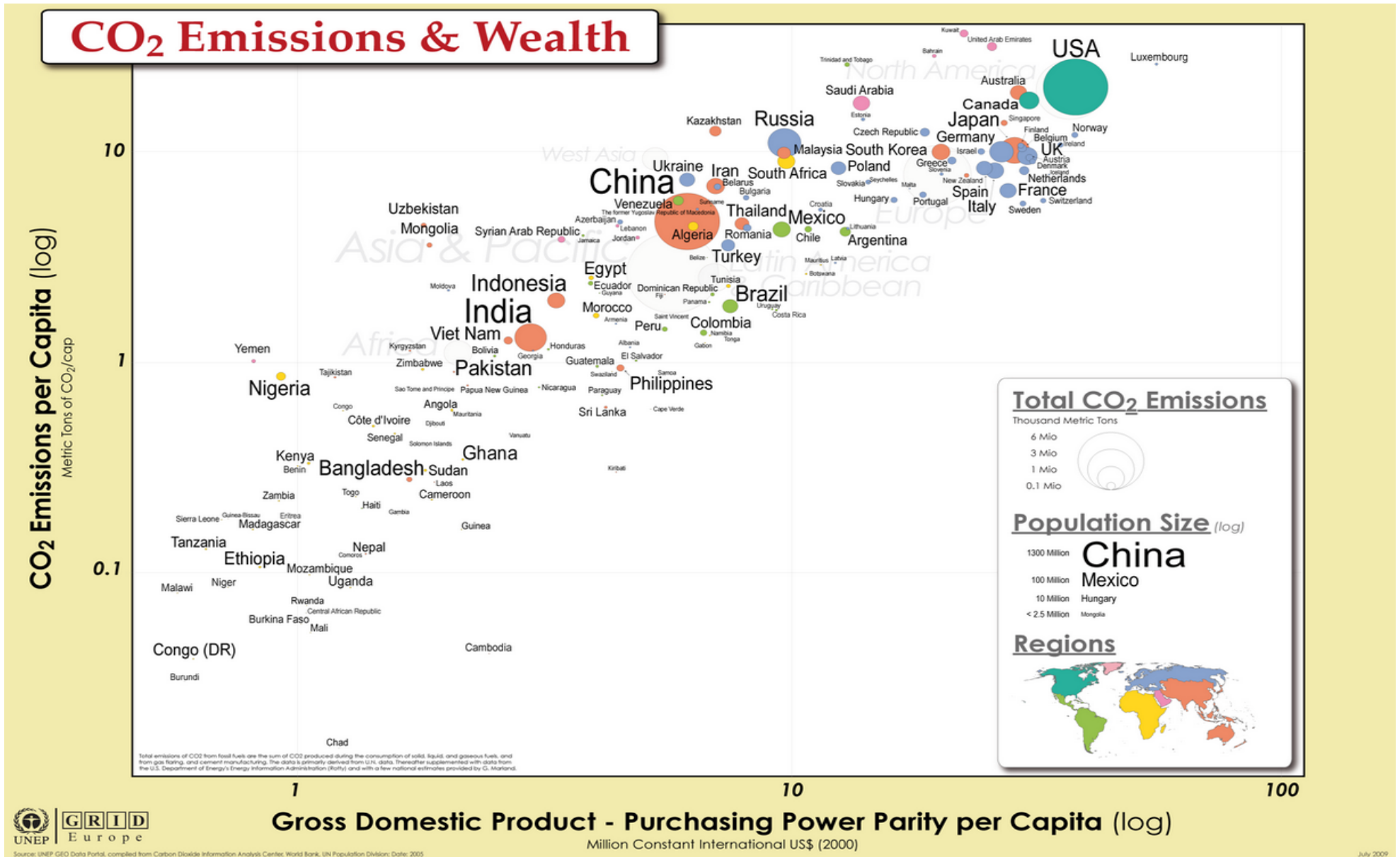


3068 pages

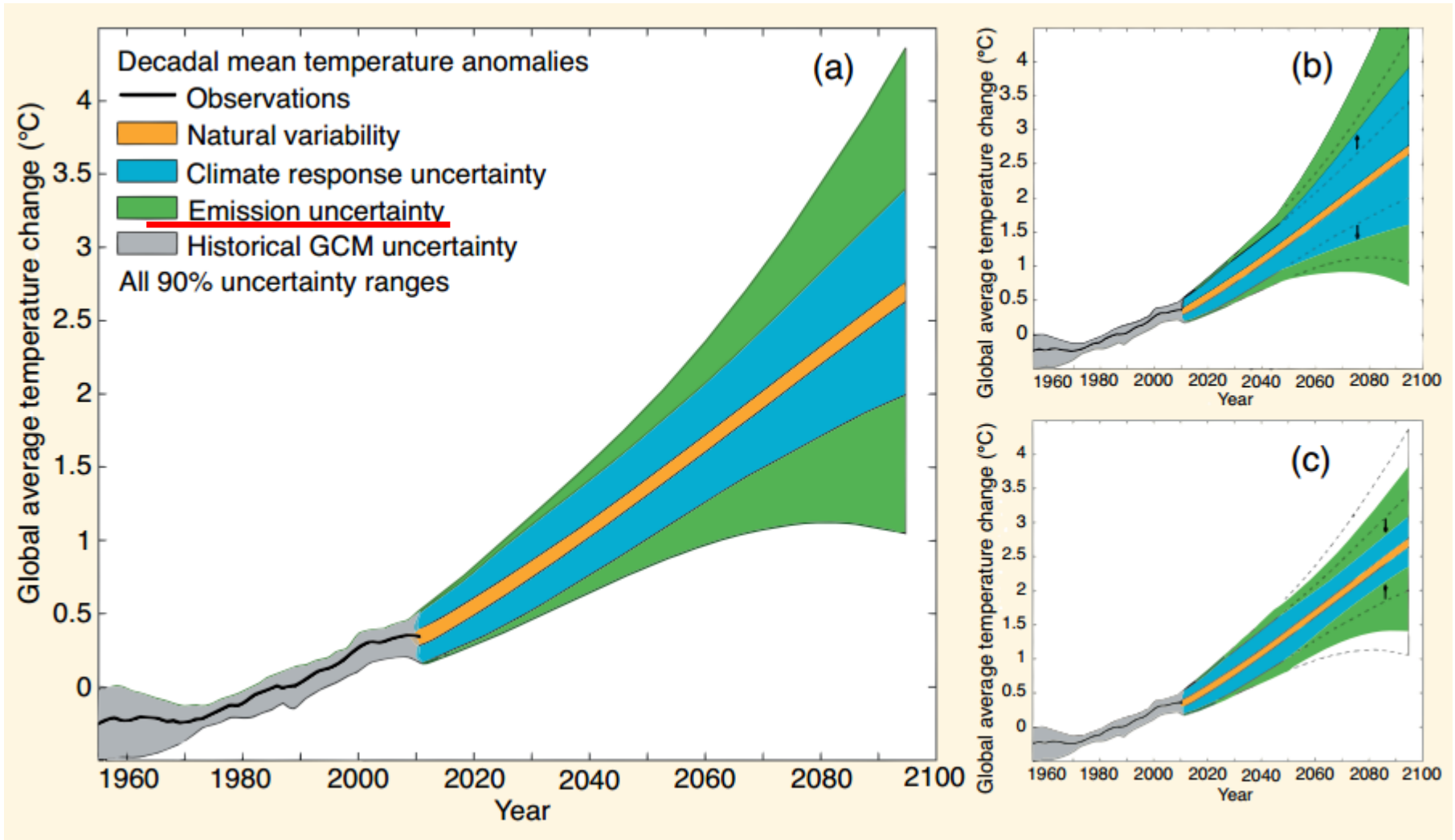


2042 pages

CO₂ and GDP



Uncertainties

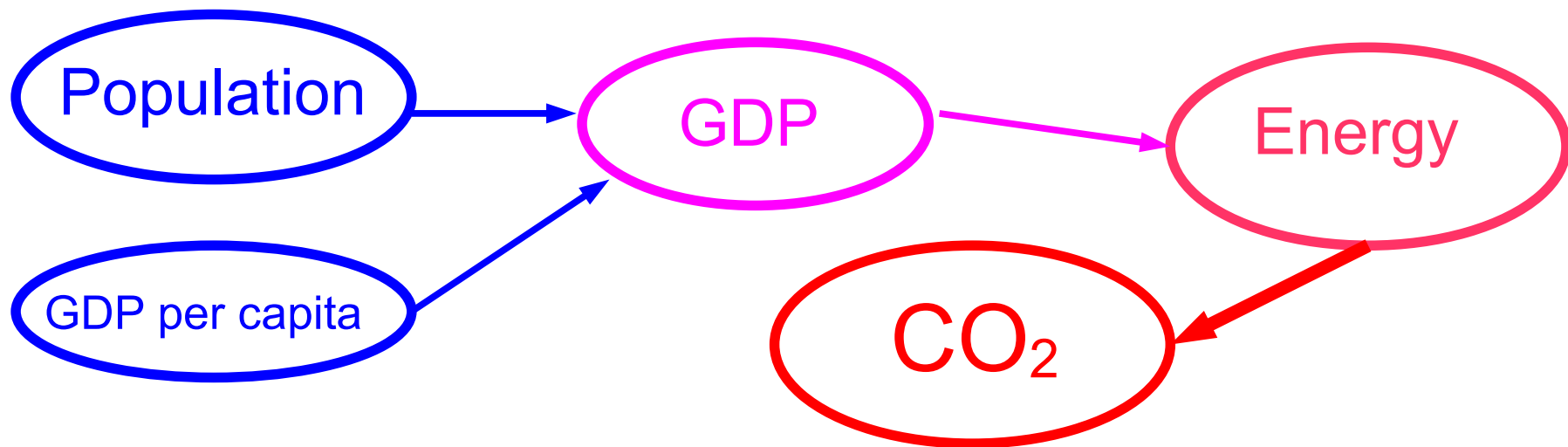


From IPCC 5th Assessment Report: Climate Change 2013

The Kaya identity

CO₂ vs economic growth

- The gross domestic product (GDP) of a given country is directly connected with its population.
- The energy consumption of a given country is directly connected with its GDP.
- Greenhouse gas emissions of a given country, as CO₂ and other pollutants, are directly related with its energy consumption.



Kaya identity

Definition

An equation that mathematically relates the factors that determine the level of human impact on climate. It was developed by Japanese energy economist Yoichi Kaya in his book *Environment, Energy, and Economy: strategies for sustainability*.

From The Dictionary of the Climate Debate (DCD)
http://www.odlt.org/dcd/ballast/kaya_identity.html

Kaya identity

$$\text{CO2} = \text{Population} \times \text{GDP_pc} \times \text{Energy_intensity} \times \text{CO2_intensity}$$

Kaya identity

$$\text{CO2} = \text{Population} \times \text{GDP}_{\text{pc}} \times \text{Energy}_{\text{intensity}} \times \text{CO2}_{\text{intensity}}$$

$$\text{CO2} = \text{Population} \times \text{GDP/Population} \times \text{Energy/GDP} \times \text{CO2/Energy}$$

Kaya identity:

A real equation or just an educated guess?

- It can be seen as a trivial identity or a tautology: it's just saying $C=C$
- It is not a real equation because all the unknowns are really not known.
- It is a useful tool to design energy and environmental policies.
- The IPCC uses it to estimate emissions from fossil fuels.
- Once an scenario is defined it is very convenient for calculating CO_2 emissions.

The modified Kaya identity

$$C = \sum_{ij} C_{ij} = \sum_{ij} P \frac{Q}{P} \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} =$$

$$P \cdot q \sum_{ij} S_i \cdot EI_i \cdot M_{ij} \cdot U_{ij}$$

Population

GDP

Sectors

Energy intensity

Energy matrix

Emission factor

i stands for the economic sector and j for the kind of fuel

- C_{ij} is the CO₂ emission in sector i for fuel j
- P is the population
- Q is the GDP of the country
- Q_i is the GDP of sector i
- E_i is the energy consumption in the sector i
- E_{ij} is the consumption of fuel j in sector i
- q is the GDP per capita
- S_i is the size of sector i
- EI_i is the energy intensity in sector i
- M_{ij} is the energy matrix of country
- $U_{ij}=U_j$ is the emission factor

The LMDI method

(logarithmic mean divisia index)

The LMDI allows to decompose the CO₂ emissions in terms of their driving forces, namely, population GDP per capita, energy intensity and energy mix (Ang B.W. and Choi K.-H., Energy Journal 18, 59-73, 1997).

Additive decomposition

$$\Delta C(t) = C(t) - C(0) = \Delta C_{pop}(t) + \Delta C_{gdp}(t) + \Delta C_{energ-int}(t) + \Delta C_{mix}(t) + \Delta C_{emission}(t)$$

$$\Delta C_{pop}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{P(t)}{P(0)}$$

Multiplicative decomposition

$$D(t) = C(t)/C(0) = D_{pop}(t) \cdot D_{gdp}(t) \cdot D_{energ-int}(t) \cdot D_{mix}(t) \cdot D_{emission}(t)$$

$$D_{pop}(t) = \exp \left(\sum_{ij} \frac{\frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)}}{\frac{C(t) - C(0)}{\ln C(t) - \ln C(0)}} \ln \frac{P(t)}{P(0)} \right)$$

LMDI for the European Union

NDC for the European Union



Update of the
NDC of the European Union and its Member States



II. NATIONALLY DETERMINED CONTRIBUTION (NDC)

27. The EU and its Member States wish to communicate the following NDC. The EU and its Member States, acting jointly, are committed to a binding target of a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990.

This NDC and accompanying information contained in the Annex replaces the 6 March 2015 submission of the EU and its Member States contained in the UNFCCC interim NDC registry and will, as of the date of the receipt of this submission by the Secretariat, be considered to be the current NDC maintained by the EU and its Member States under Article 4 of the Paris Agreement.

NDC for the European Union



Update of the
NDC of the European Union and its Member States



SUBMISSION BY SPAIN AND THE EUROPEAN COMMISSION ON BEHALF OF THE
EUROPEAN UNION AND ITS MEMBER STATES

Madrid, 16 October 2023

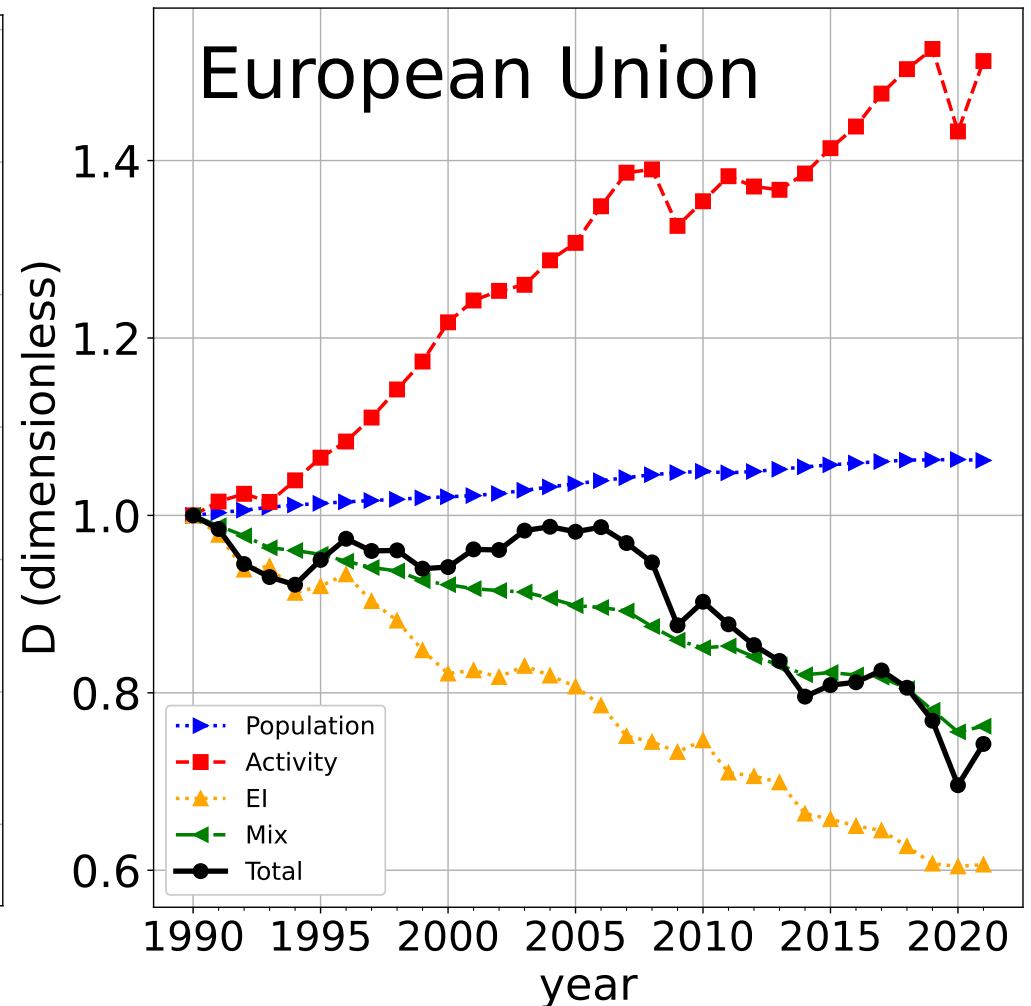
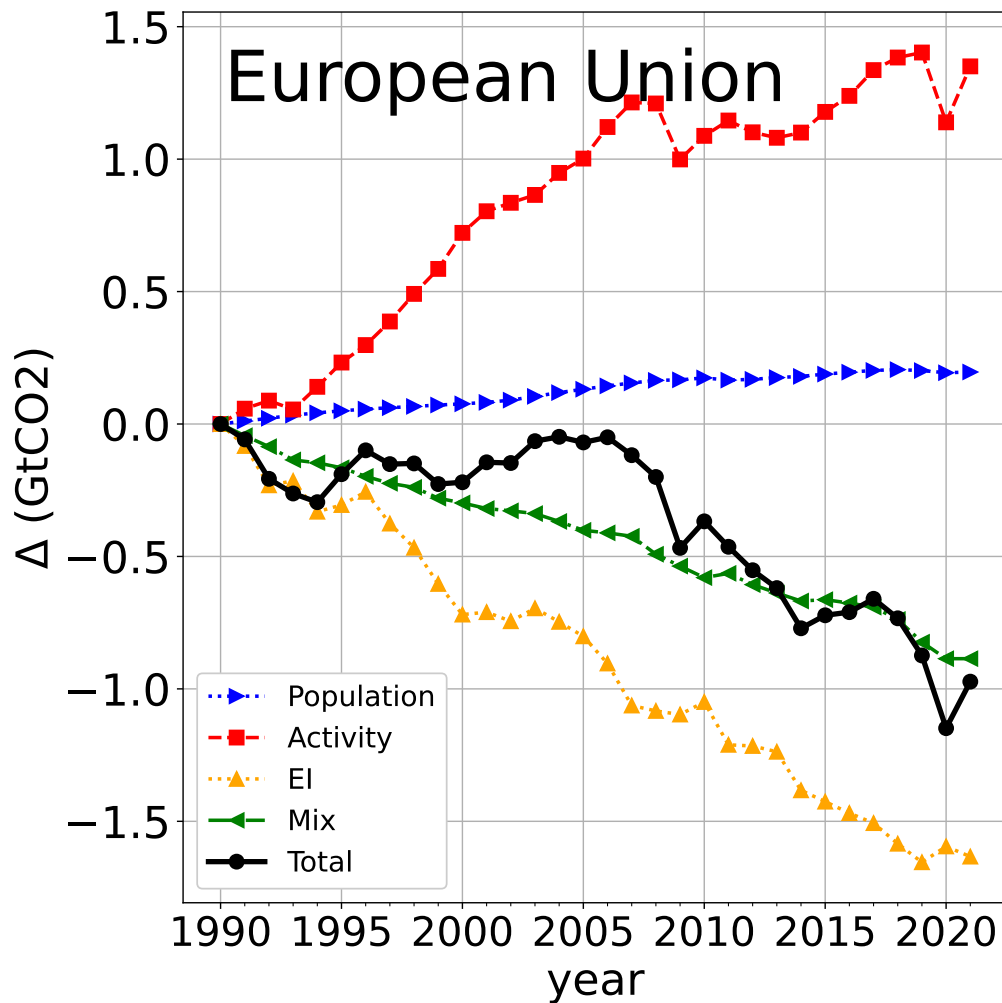
savings through an enhanced target to **reduce final energy consumption at EU level by 11.7% in 2030** and a new target for **increasing renewable energy in final energy consumption of at least 42.5% by 2030**, with an additional 2.5% indicative top up that would allow to reach 45%.

With regard to **new cars and vans**, the EU adopted legislation to reduce **55% of CO₂ emissions for new cars and 50% for new vans from 2030 until 2034**, and for **100% CO₂ emissions reductions from 2035 for new cars and vans**.

The update is being treated in COP28 in Qatar right now

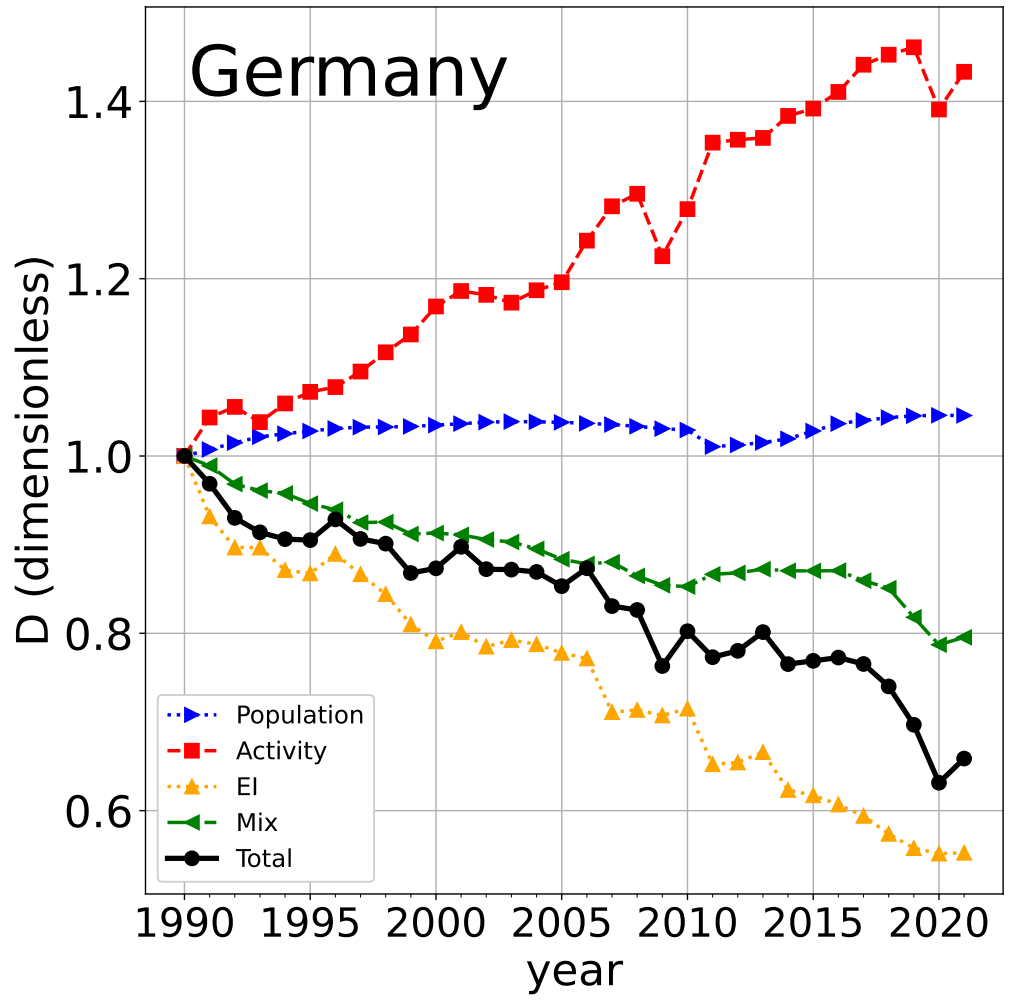
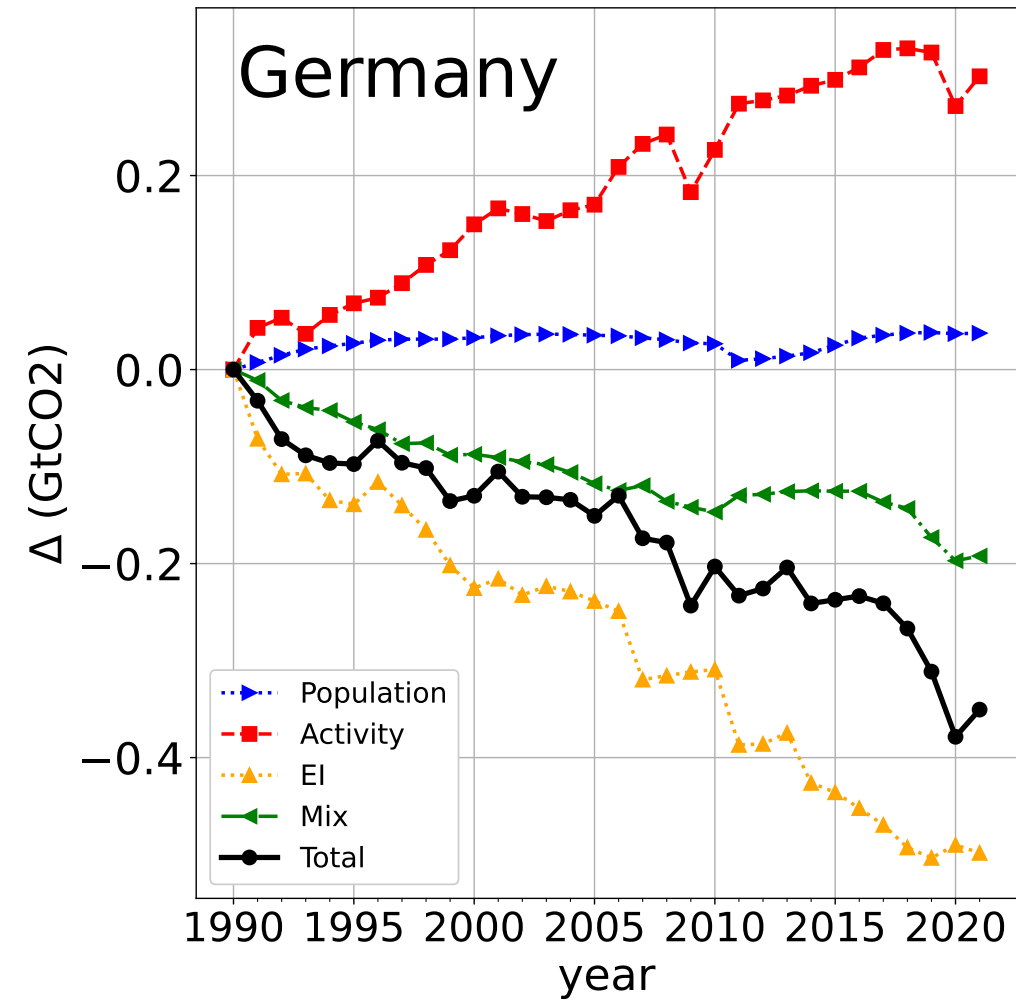
Results

The European Union (EU27): 3.8 Gt CO₂ in 1990



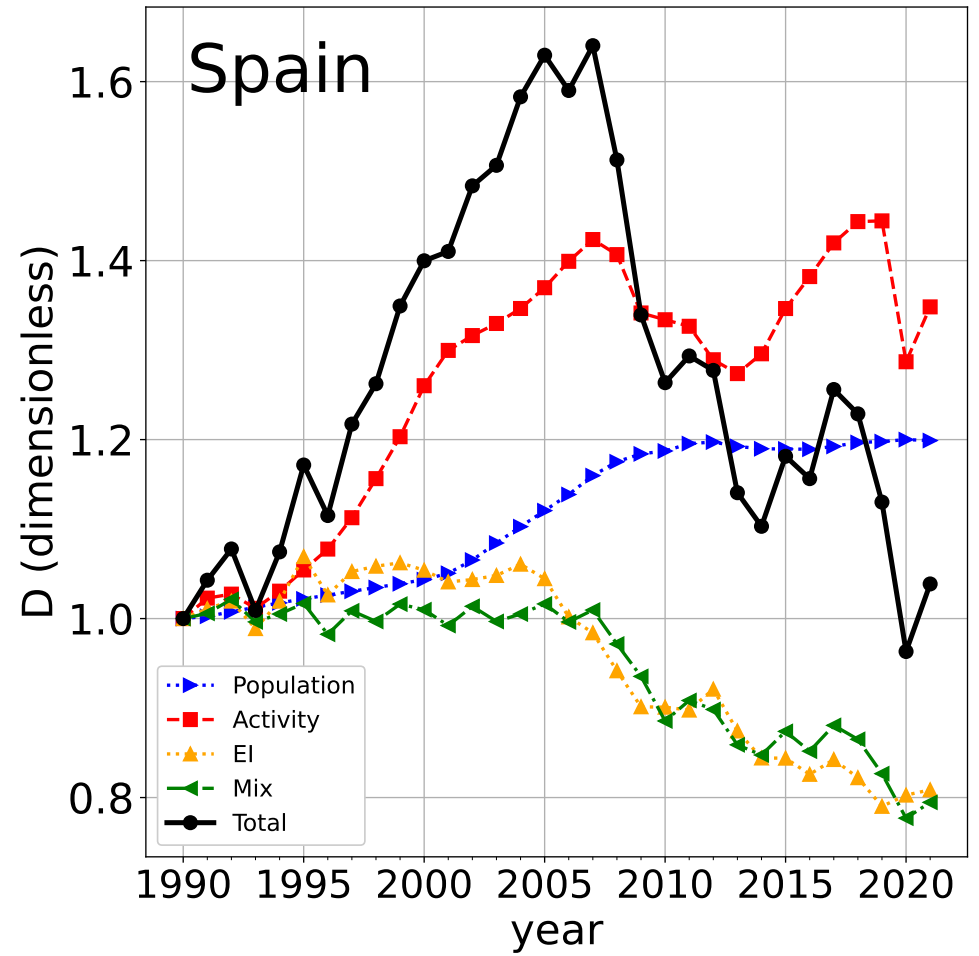
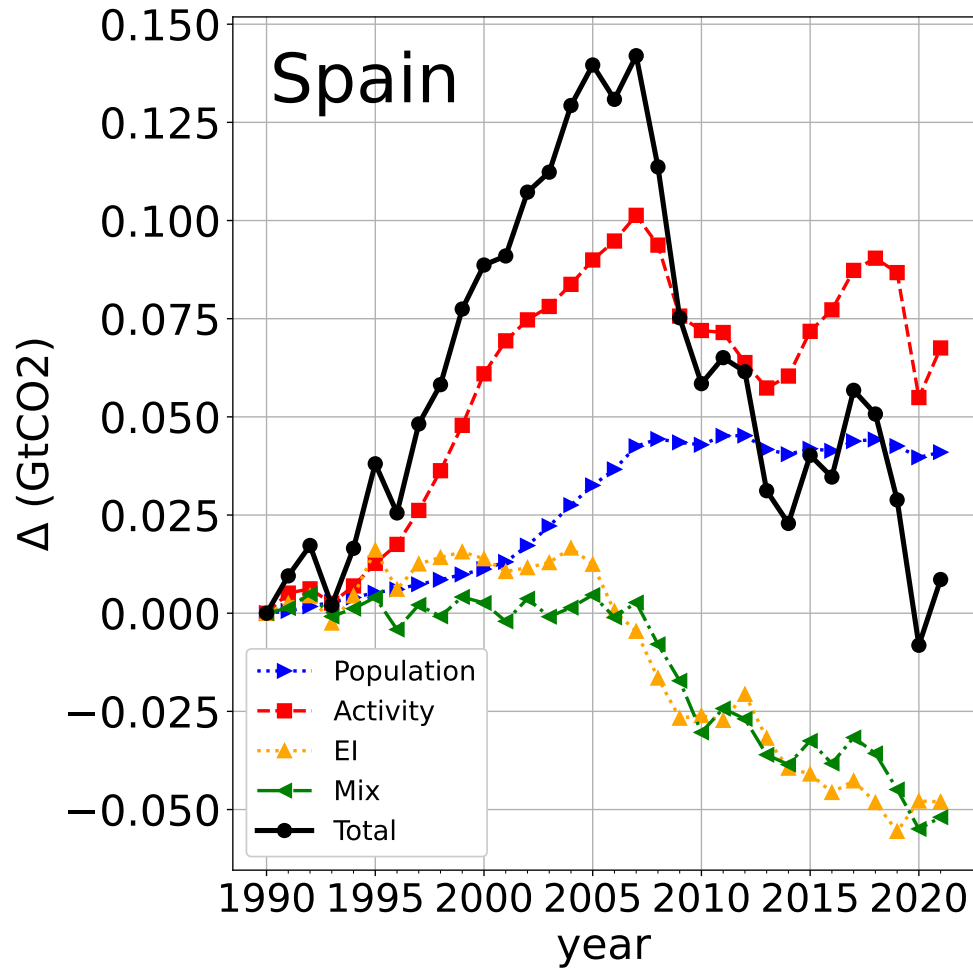
Results

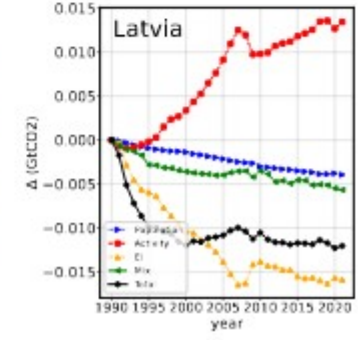
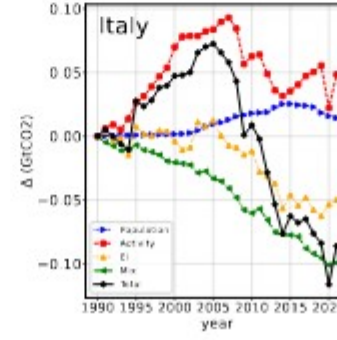
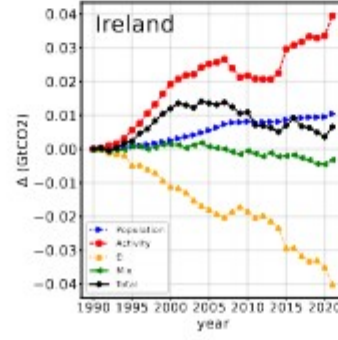
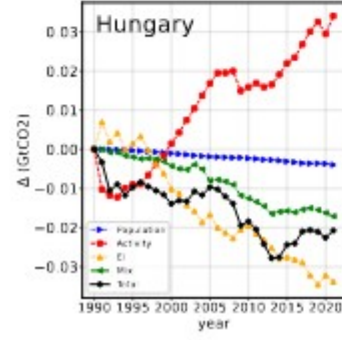
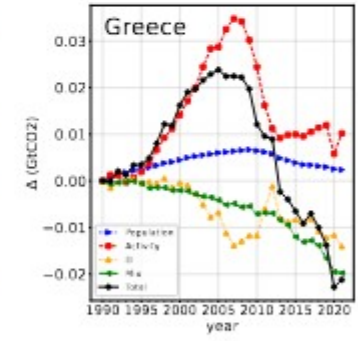
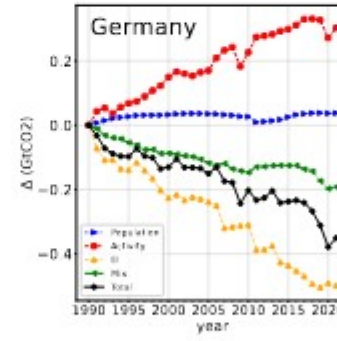
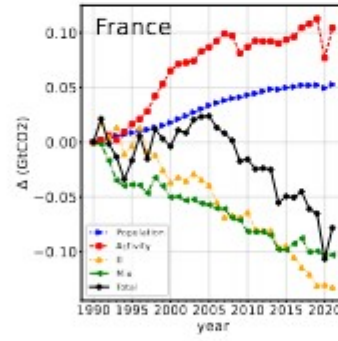
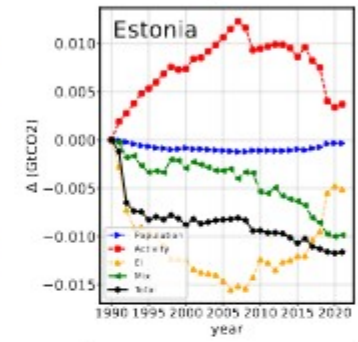
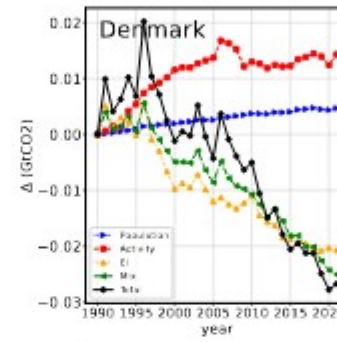
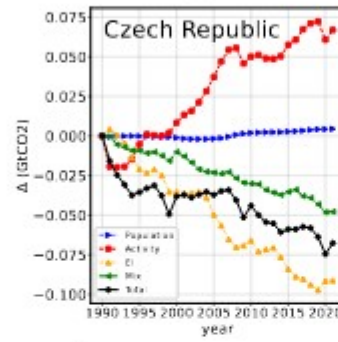
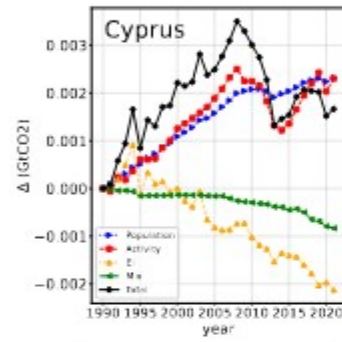
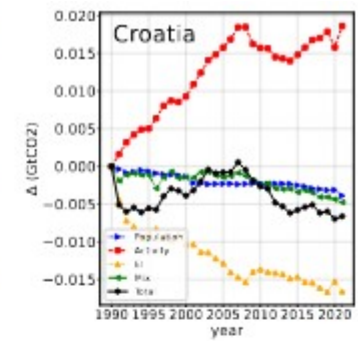
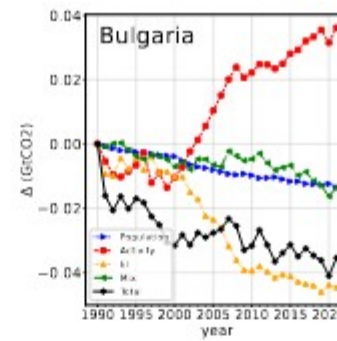
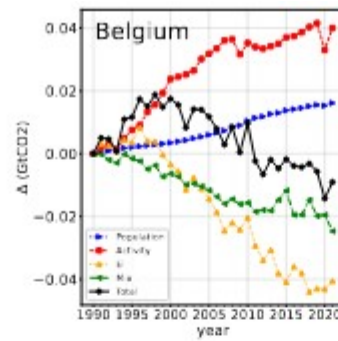
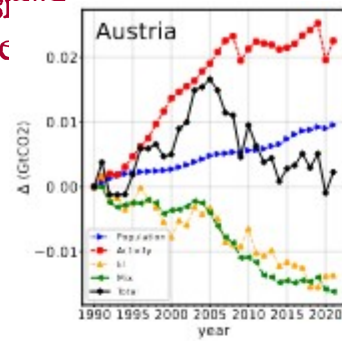
Germany

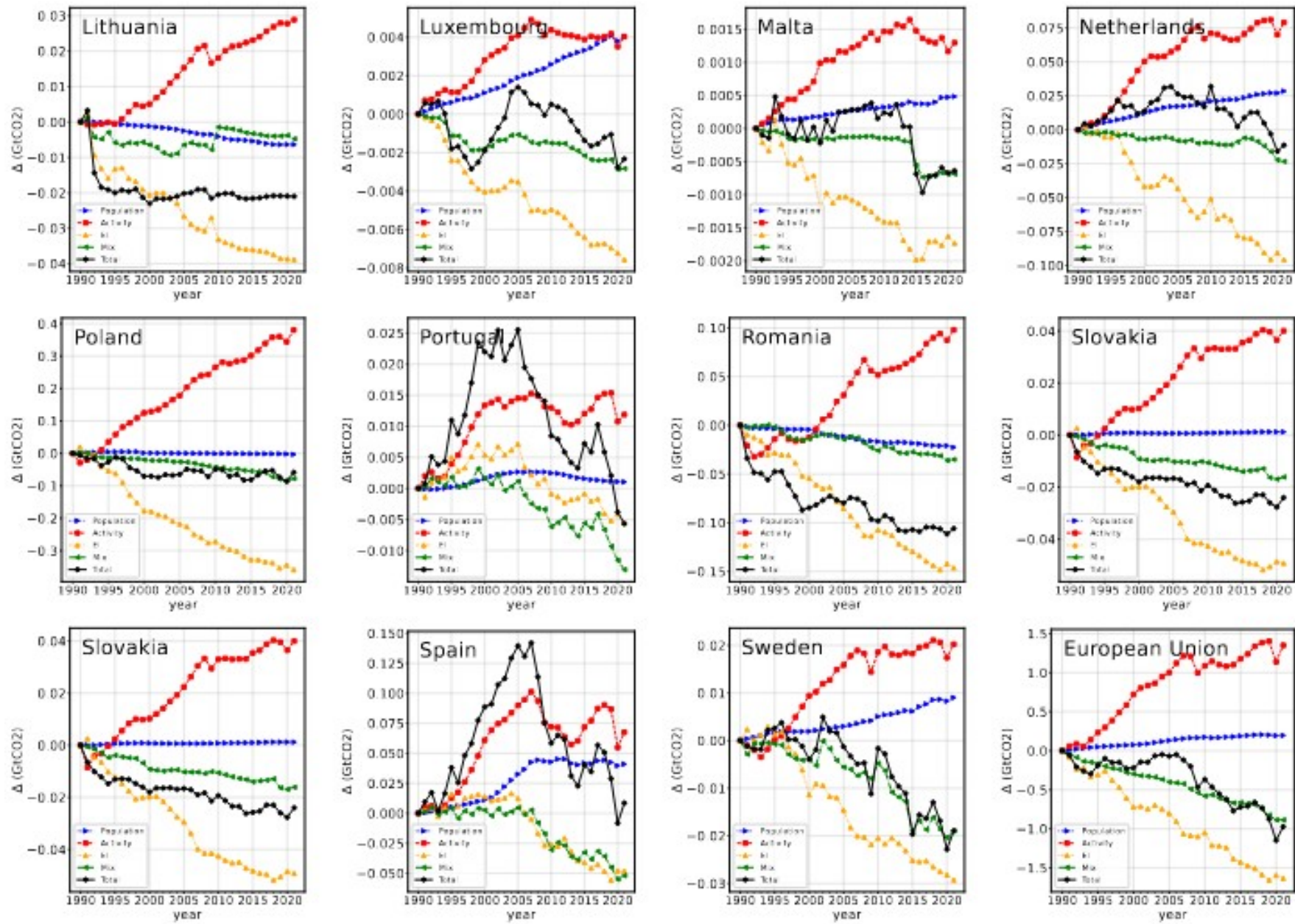


Results

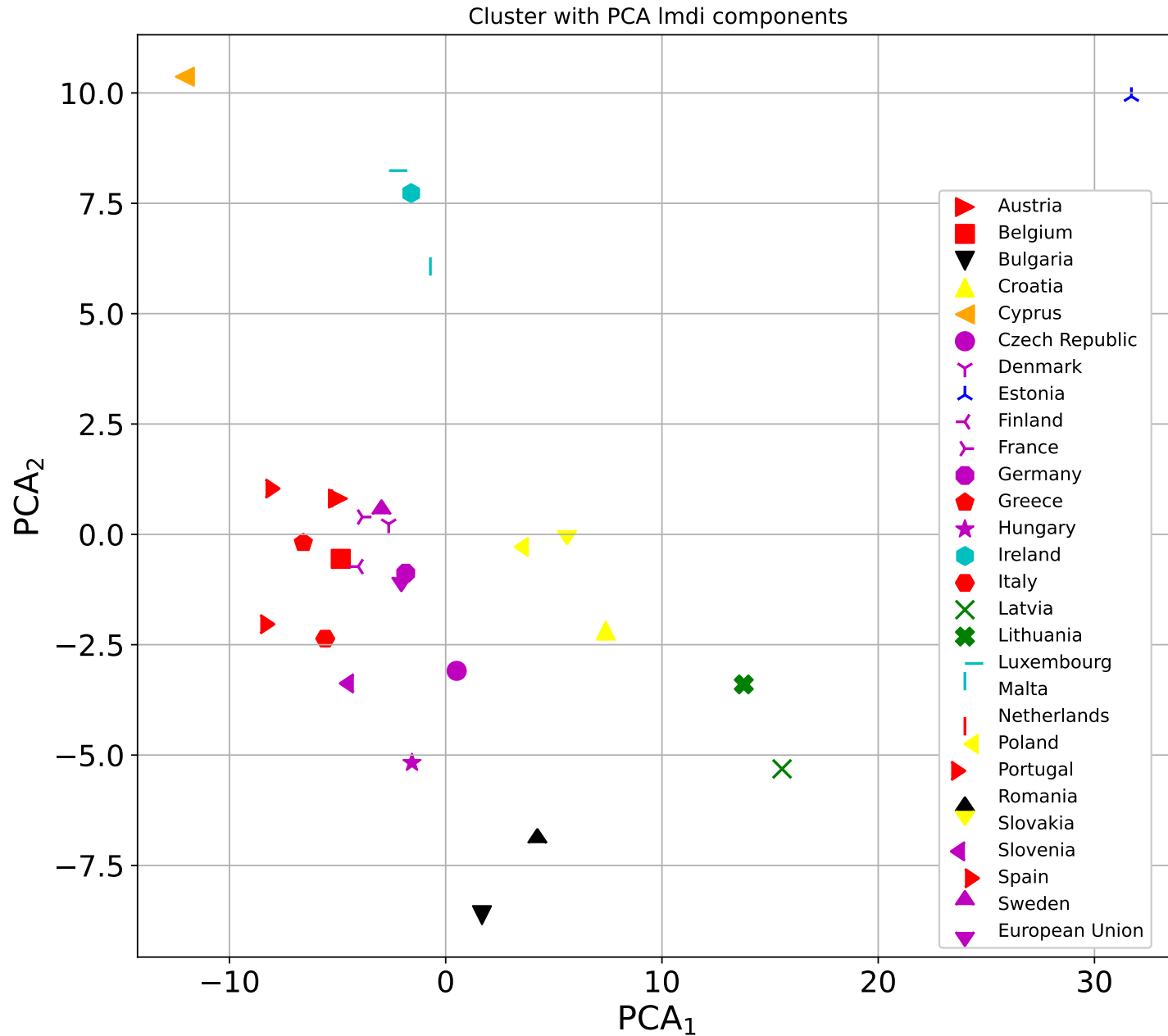
Spain







A principal component plus cluster analysis



Granger causality analysis: Application to the large emitters

Granger causality analysis

$$CO_{2t} = \alpha_1 + \sum_{i=1}^{l+d_{max}} \beta_{1i} CO_{2t-i} + \sum_{j=1}^{l+d_{max}} \gamma_{1j} GDP_{t-j} + \varepsilon_{1t}$$

$$GDP_t = \alpha_2 + \sum_{i=1}^{l+d_{max}} \beta_{2i} GDP_{t-i} + \sum_{j=1}^{l+d_{max}} \gamma_{2j} CO_{2t-j} + \varepsilon_{2t}$$

where l is the optimal lag structure and d_{max} corresponds to the maximum order of integration for the variables considered in the model

To test the Granger causality between the two variables selected, if $\sum \gamma_{1j} \neq 0$ this suggests that GDP Granger causes CO₂. Similarly, if $\sum \gamma_{2j} \neq 0$, CO₂ Granger causes GDP. **A Granger causality relationship only supposes that the first variable can be used to forecast the second one reliably.**

The six major emitters

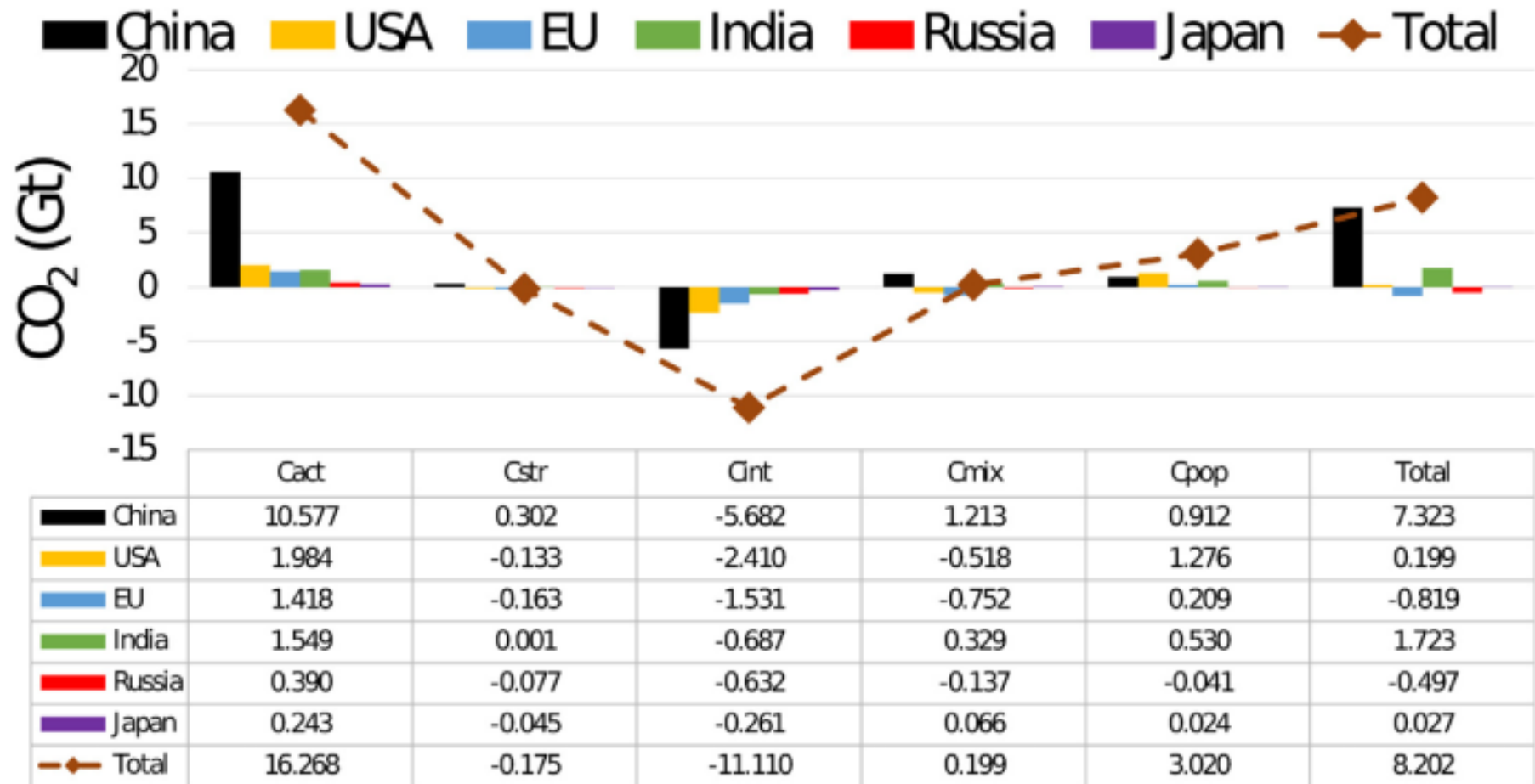
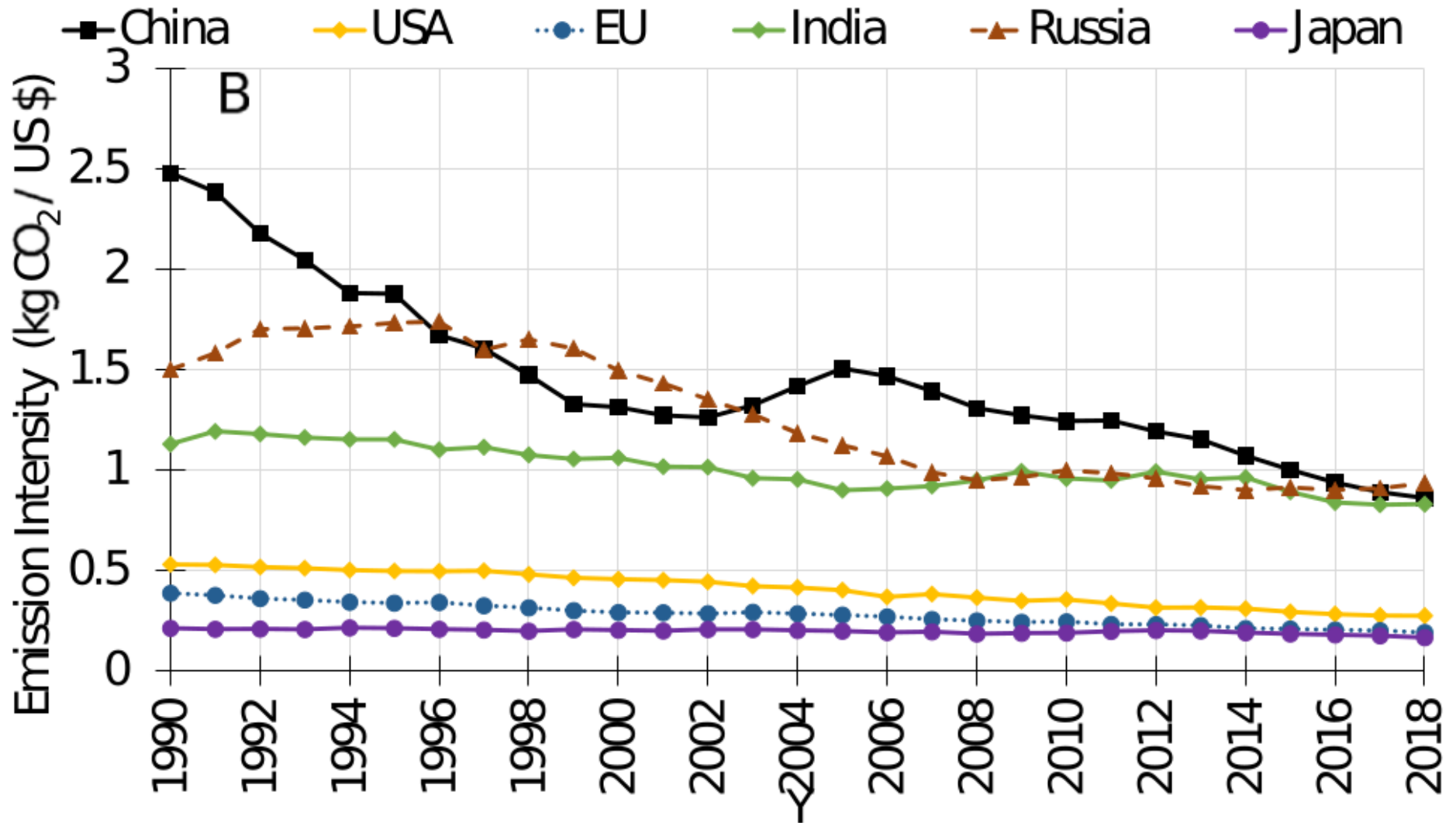
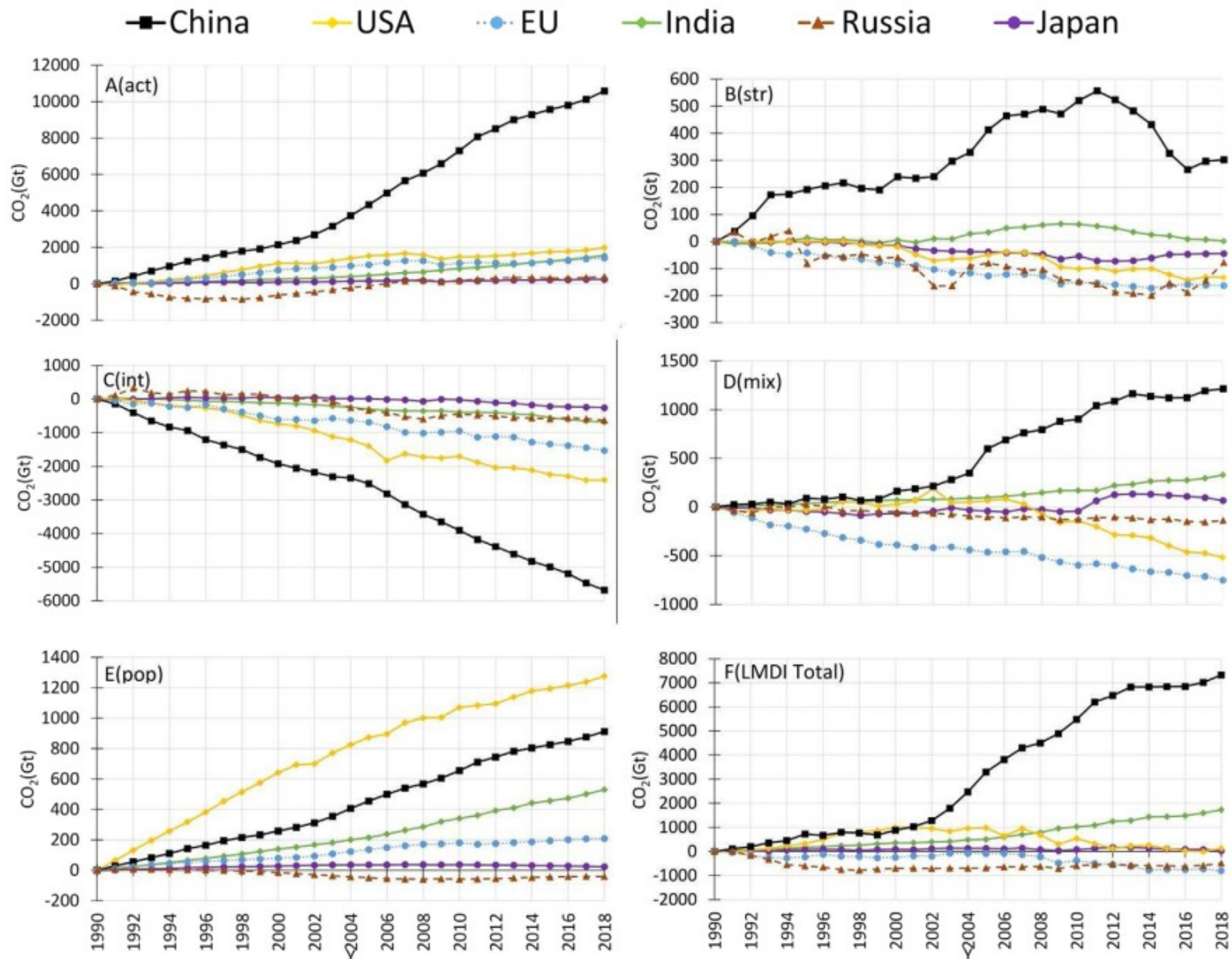


Fig. 7. Additive CO₂ LMDI decomposition for the whole period 1990–2018 and the six analyzed countries.

The emission intensity



The six major emitters

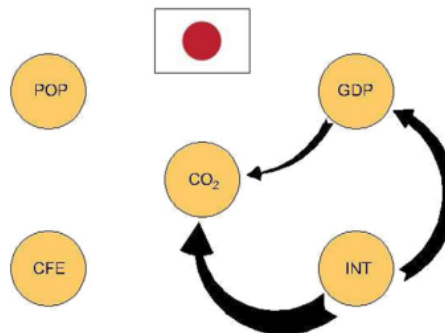
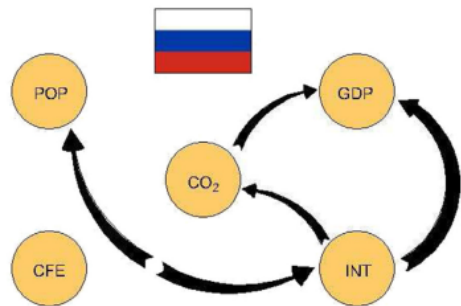
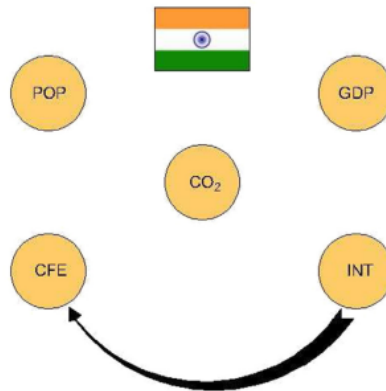
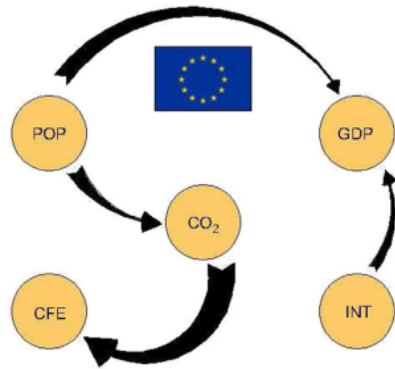
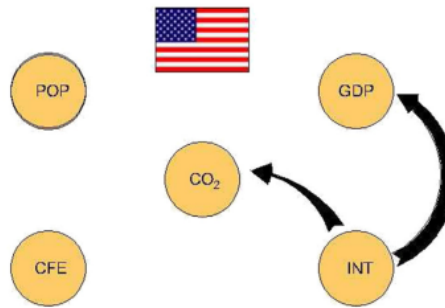
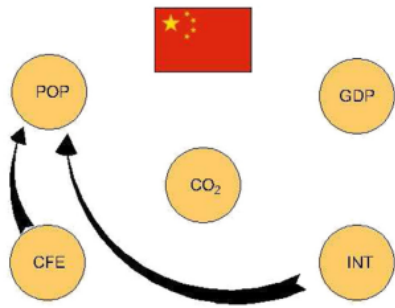


Granger causality analysis

Coefficients from Toda–Yamamoto Granger causality analysis. *Significance at 10% level, **Significance at 5% level, and ***Significance at 1% level.

α	β	China		USA		EU		India		Russia		Japan	
		$\alpha \rightarrow \beta$	$\alpha \leftarrow \beta$	$\alpha \rightarrow \beta$	$\alpha \leftarrow \beta$	$\alpha \rightarrow \beta$	$\alpha \leftarrow \beta$	$\alpha \rightarrow \beta$	$\alpha \leftarrow \beta$	$\alpha \rightarrow \beta$	$\alpha \leftarrow \beta$	$\alpha \rightarrow \beta$	$\alpha \leftarrow \beta$
GDP	CO ₂	2.773	6.007	4.468	2.080	0.187	0.000	0.000	0.001	1.841	4.969*	5.190*	2.77
CFE	CO ₂	0.779	1.279	4.372	0.721	0.124	6.470**	0.089	1.756	0.193	0.020	1.286	3.04
POP	CO ₂	0.136	1.777	0.778	2.388	11.799*	1.090	0.000	3.177	1.234	1.926	0.297	0.76
INT	CO ₂	2.981	3.253	16.294*	3.455	1.456	0.323	0.633	0.043	6.223*	4.759	58.450**	0.85
CFE	GDP	0.297	4.740	0.279	1.423	0.004	2.066	0.070	0.485	0.012	0.098	6.688	2.99
POP	GDP	0.036	1.119	2.167	3.809	10.739*	0.658	0.000	0.067	0.770	4.709	6.162	2.49
INT	GDP	1.805	3.528	11.785*	5.874	3.267*	0.095	0.128	0.025	12.439*	6.034	9.296**	1.71
POP	CFE	0.097	12.527**	0.369	1.295	0.917	3.310	0.000	11.638	0.472	0.943	0.672	2.14
INT	CFE	0.920	0.917	2.854	0.252	0.351	0.025	5.331*	0.445	0.012	0.004	2.286	1.77
INT	POP	20.086**	0.118	6.479	0.400	1.036	5.300	1.379	0.000	9.080**	9.308*	3.479	5.32

Granger causality analysis

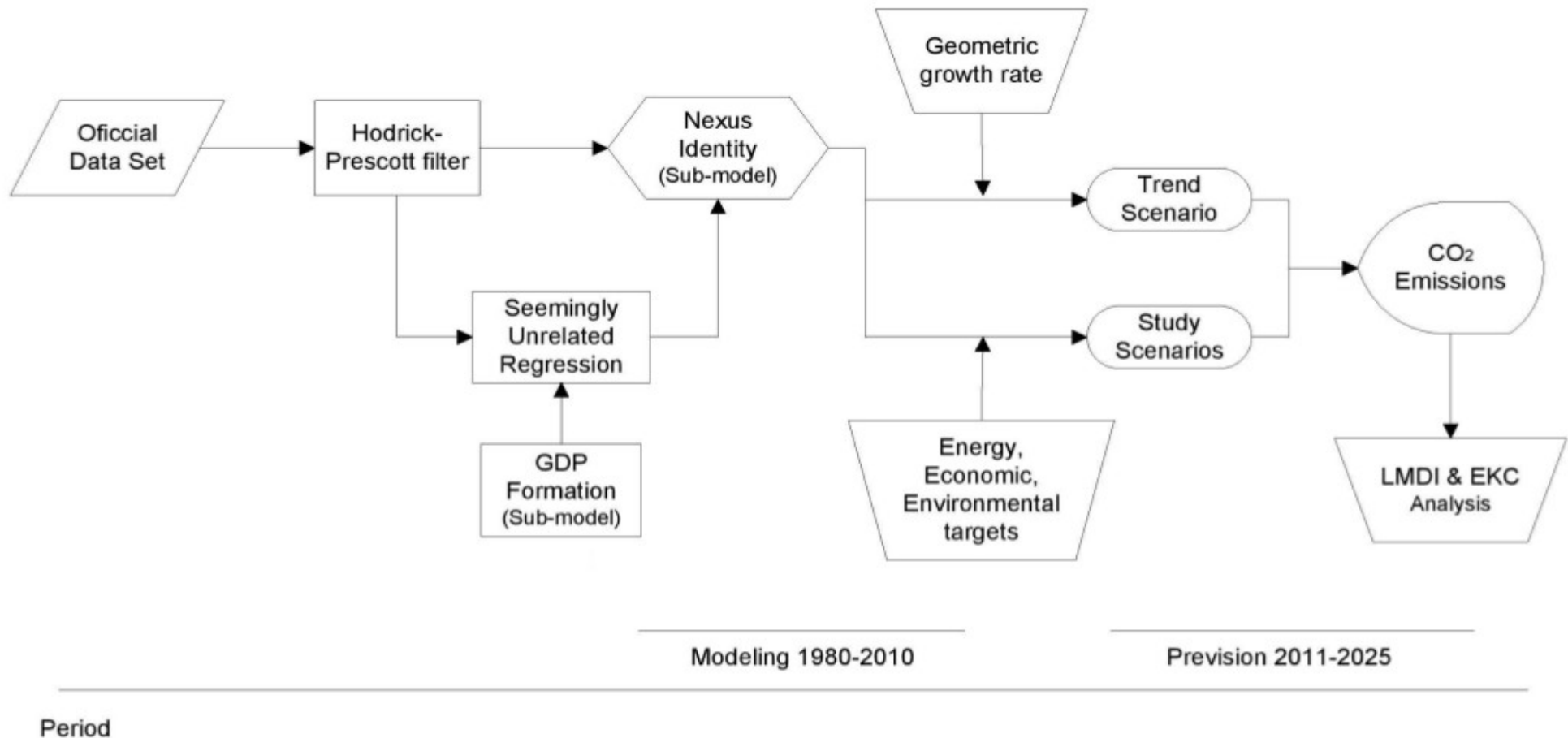


No clear conclusions can be obtained:

- Only in Japan GDP is Granger causing CO₂.
- In USA energy intensity is Granger causing CO₂.
- In EU CO₂ is Granger causing free-carbon energies.
- In Russia CO₂ is Granger causing GDP.

A simple model for forecasting

General structure of this analysis



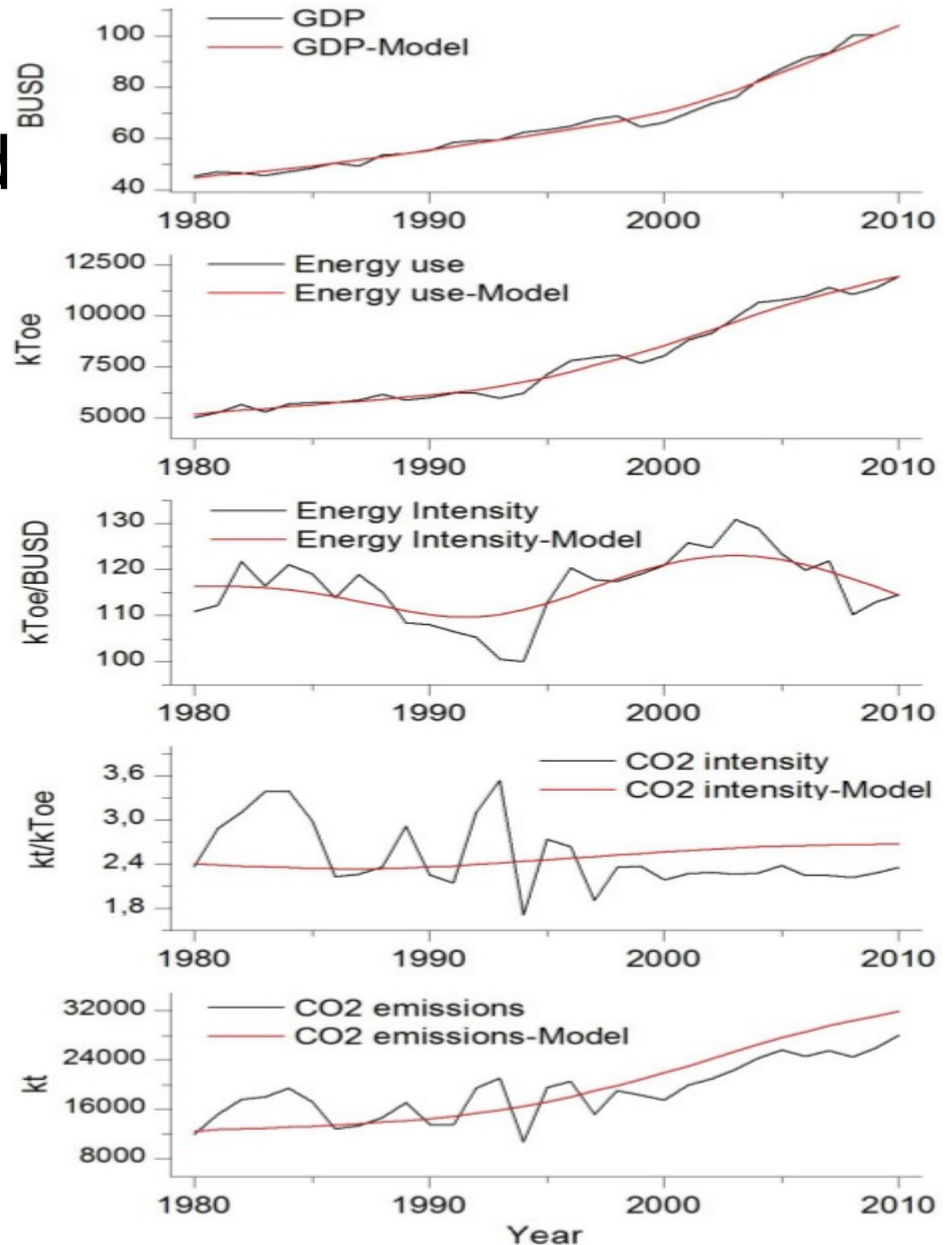
From A. Robalino PhD Thesis

Hodrick-Prescott filter and validation

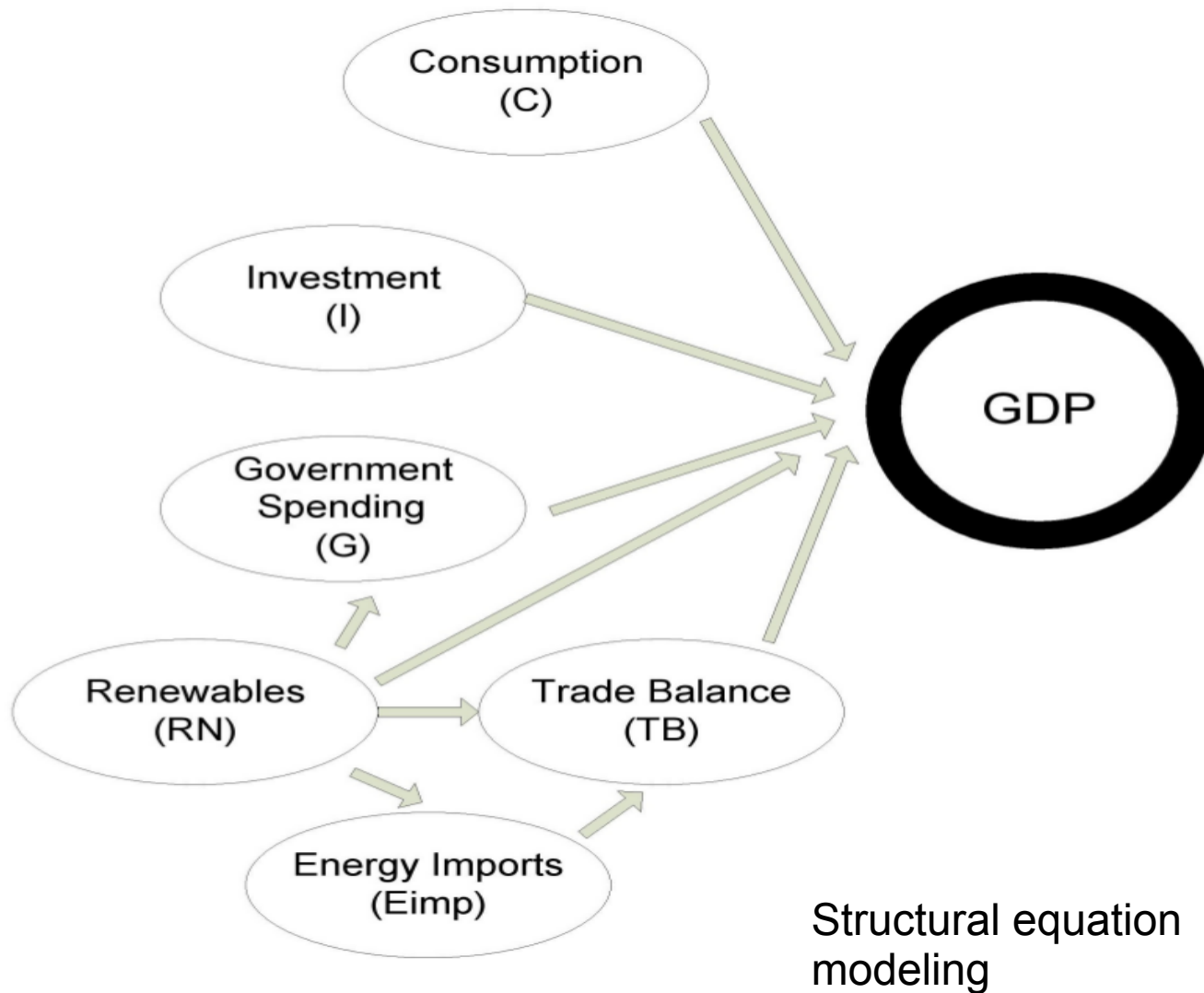
$$MAPE(\%) = \frac{1}{n} \sum_{t_1}^n \left| \frac{A_t - F_t}{A_t} \right| \times 100.$$

VARIABLE	MAPE(%)
GDP	2.2
Energy consumption	3.3
Energy intensity	3.2
CO ₂ intensity	16
CO ₂ emission	17

From A. Robalino PhD Thesis



Economic submodel



From A. Robalino PhD Thesis



Economic submodel

$$GDP = C + I + G + X - M,$$

C: consumption, I: investment, G: government spending,
X: exports, M: imports.

$$Q = a_1 \cdot I + a_2 \cdot TB + a_3 \cdot C + a_4 \cdot Eimp + a_5 \cdot RN + \epsilon_1$$

$$I = b_1 \cdot RN + b_2 \cdot C + \epsilon_2,$$

$$TB = c_1 \cdot Eimp + c_2 \cdot RN + \epsilon_3,$$

$$Eimp = d_1 \cdot RN + \epsilon_4,$$

$$C = f_1 \cdot Eimp + f_2 \cdot TB + \epsilon_5,$$

Eimp: energy imports, TB=X-M, RN: renewable energy.

Economic submodel

Variable	GDP ^b	I	TB	C	Eimp
I ^c	1.16*** (5.11)			-6.07*** (-41.44)	
TB ^d	0.99*** (3.46)				
C ^e	1.21*** (7.70)	0.50*** (100.40)			
E _{imp} ^f	0.05*** (2.66)		0.01*** (4.14)	-0.27*** (-100.17)	
RN ^g	-0.50*** (-4.44)	-0.84*** (-5.40)	0.04 (0.28)		-36.79*** (-5.47)

^a *** represents significance at the 1% level and numbers in parentheses are *t*-statistics.

Estimation Method: SUR. Sample: 1980-2010. Included observations: 155.

^b GDP in 10¹⁰ USD. ^e C in 10¹⁰ USD.

^c I in 10¹⁰ USD. ^f Eimp in 10⁶ toe.

^d TB in 10¹⁰ USD. ^g RN in 10⁶ toe.

How do we extrapolate?

- We use the extreme simple *geometric growth rate* formula:

$$y(t) = y(t-1) \cdot (1 + r_y)$$

- Where $y(t)$ is whatever variable to be extrapolated.
- r_y is defined through the scenario.

$$Q(t) = a_1 I(t) + a_2 TB(t) + a_3 C_a(t) + a_4 E_{imp}(t) + a_5 RN(t-1),$$

$$E_j(t) = \sum_i S_i(t) \cdot EI_i(t) \cdot M_{ij}(t) \cdot GDP(t),$$

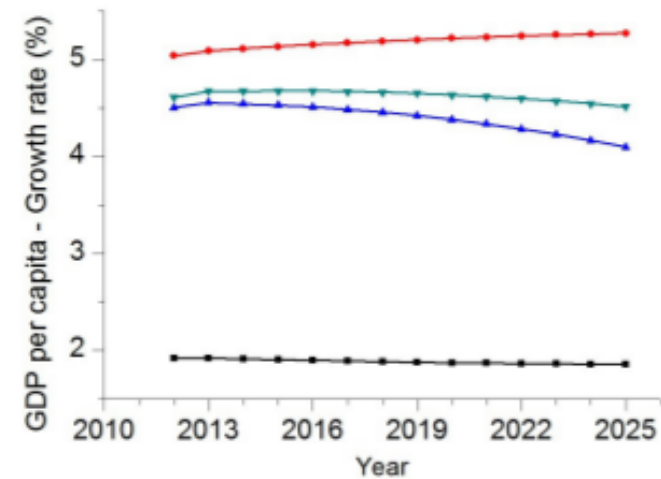
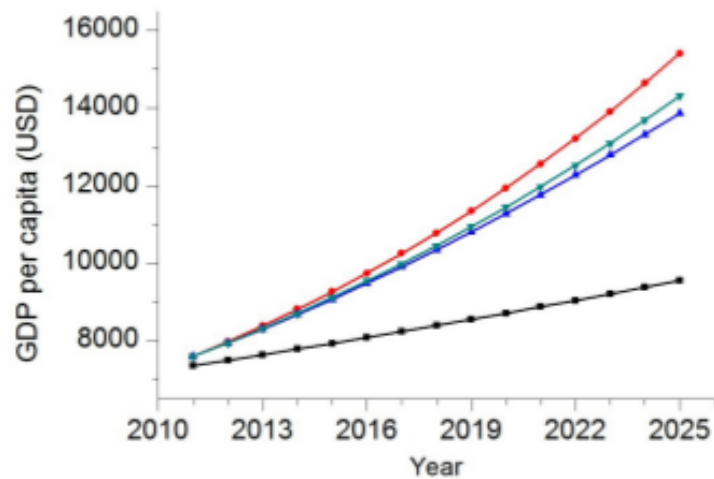
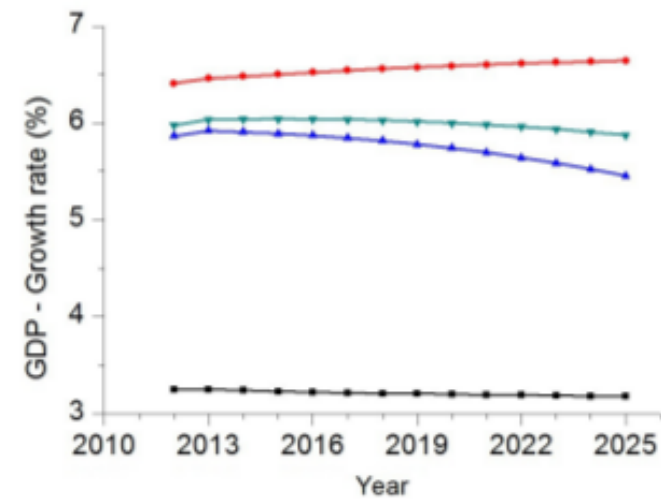
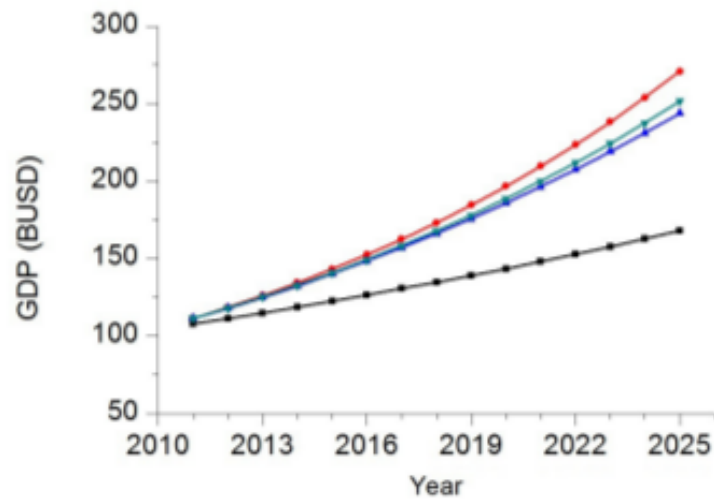
Defining a scenario

- Define a target for the GDP at the target year.
- Define a target for the use of renewable energy.
- Define a target for the energy intensity.

Scenarios

- Baseline scenario (SC-1): GDP, energy matrix, and productive sectoral structure evolve following a smooth trend.
- SC-2: The GDP increases up to the double of the reference GDP (2010) by 2025. The rest of variables evolve as in SC-1.
- SC-3: the use of renewable energy passes from 12% in 2011 to 23% in 2025. The rest of variables evolves as in SC-2.
- SC-4: the energy intensity drops 1% yearly. The rest of variables evolves as in SC-3.

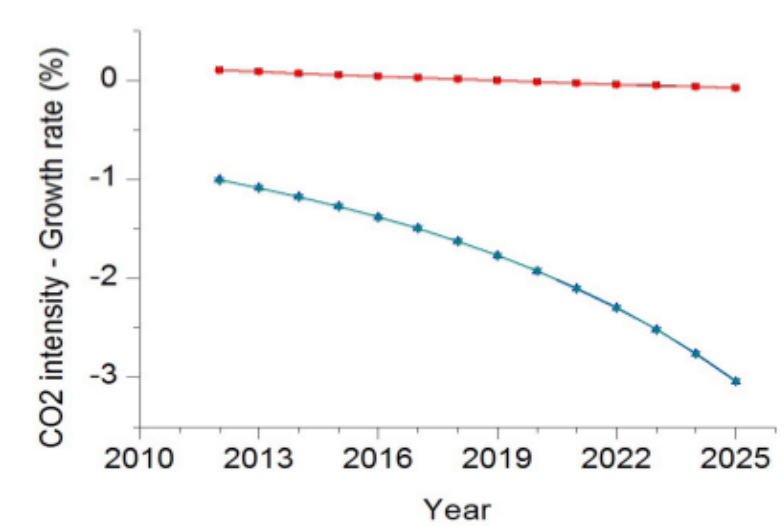
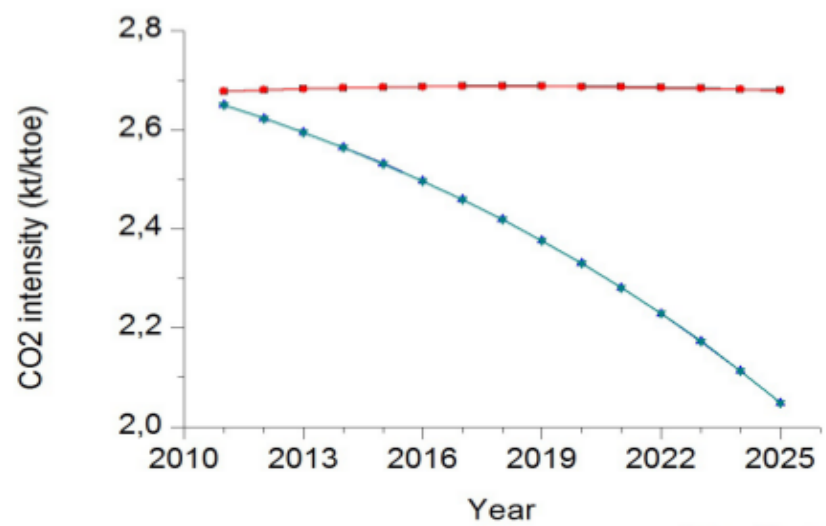
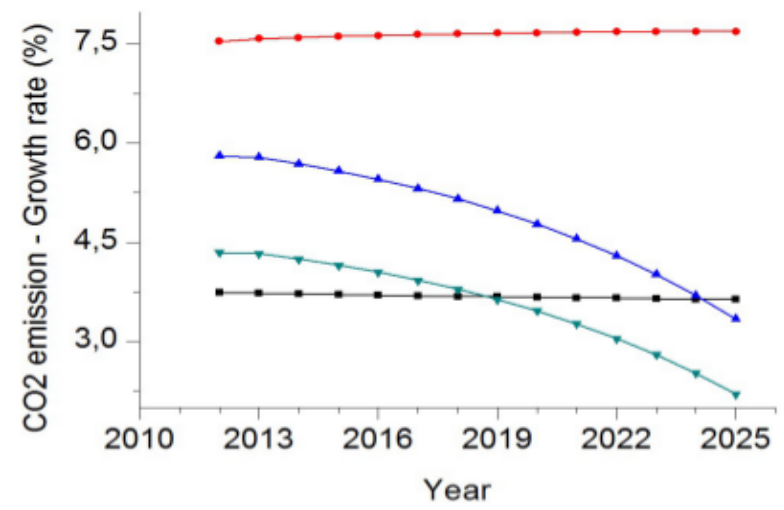
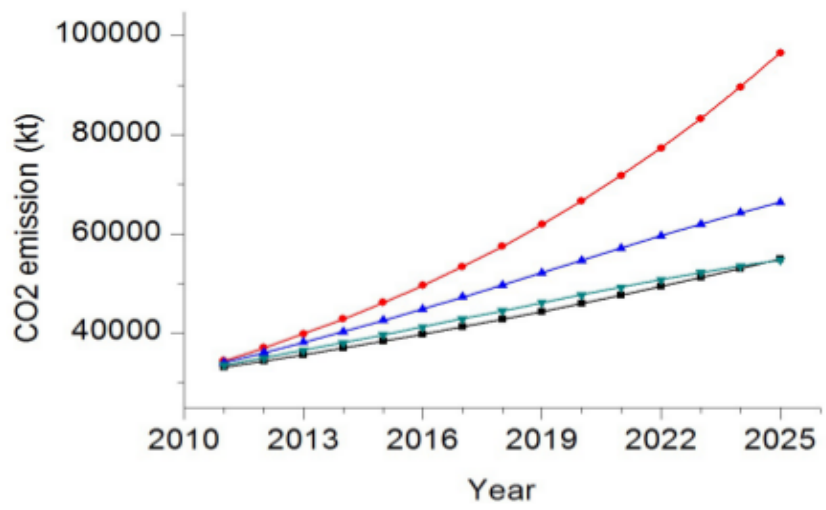
Estimations:GDP



■ BS ● SC-2 ▲ SC-3 ▼ SC-4

From A. Robalino PhD Thesis

Estimations: emissions



■ BS ● SC-2 ▲ SC-3 ▼ SC-4

From A. Robalino PhD Thesis

Summary and conclusions

- There exists a direct relationship between global warming and economic activity, mediated through the use of energy.
- The time series for the period 1990-2021 for the 27 members of the EU have been studied (not shown here).
- It has been qualitatively shown how energy intensity and the use of renewable energies (energy matrix) are both key factors to mitigate CO₂ emissions.
- To fulfill the European NDC it is compulsory to carry out a stronger effort.
- This kind of analysis is expected to be useful for policymakers.
- The importance of CO₂ emissions of the EU is relatively modest compared with the ones of other countries.
- Results from the Granger causality analysis are not conclusive.
- It is possible to simply forecast CO₂ emissions defining an scenario.

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- Manuel Hermoso (professor U. Jaén, Spain)
- Julio Terrados (professor U. Jaén, Spain)

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