Εθνικό Μετσόβιο Πολυτεχνείο
Σχολή Ηλεκτρολόγων Μηχανικών
και Μηχανικών Υπολογιστών
Τομέας Τεχνολογίας Πληροφορικής και
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Αποδοτική εξισορρόπηση αδειών εκπομπής αερίων θερμοκηπίου στον μηχανισμό EU-ETS

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ΚΩΝΣΤΑΝΤΙΝΟΣ ΠΑΠΑΔΟΠΟΥΛΟΣ

Επιβλέπων : Δημήτριος Φωτάκης
Καθηγητής Ε.Μ.Π.

Αθήνα, Νοέμβριος 2024

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Αθήνα, Νοέμβριος 2024

Κωνσταντίνος Παπαδόπουλος

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Περιεχόμενα

Κατάλογος σχημάτων

Κατάλογος πινάκων

List of Algorithms

Εκτεταμένη Ελληνική Περίληψη

0.1 Εισαγωγή

Εδώ θα μπει κάποια εισαγωγή.

0.2 Επόμενα

Chapter 1

Fair Distribution - Fair Division

1.1 intro + meaning

1.2 principles

1.3 theory + main concepts of achieving fairness

1.4 How fairness consideration influence policy decisions

Chapter 2

EU ETS

2.1 basic opearation + intro to the system

check koromilas

2.2 Importance of initial allocation

handbook

2.3 Allocation through the years / Phases

2.4 Connection with fair division

2nd paragraph cest 23

2.5 Fairness in EUETS

3rd paragraph cest 23

2.6 Applications of different fairness principles theoretically

Τα 4 του Moulin ανάπτυξη στο πώς θα έμοιαζαν για εμάς.

2.7 existing allocation methods (auction, grandfathering...) with reference to fairness principles

Chapter 3

Understanding EU ETS through clustering

3.1 Motivation & First Experiment Setup

3.1.1 Introduction

Γενική εισαγωγή στο γιατί είναι σημαντικό να μελετήσουμε την δικαιότητα στο EU ETS.

1. Παίζοντας με τα δεδομένα, έγιεν σαφές πως οι δωρεάν άδειες δεν δίνονταν με ομοιογενή τρόπο μεταξύ των χωρών.
2. Το σύστημα προσπαθεί να είναι δίκαιο, επομένως, είναι σημαντικό να φανεί αν χώρες που μοιάζουν αντιμετωπίζονται με τον ίδιο τρόπο.
3. Αποδοτικότητα στο σύστημα;
4. Συνέχεια της διπλωματικής του παναγιώτη που χώριζε τις εταιρείες σε αρχηγούς και ακόλουθους.

3.1.2 Initial Experiment Design

Objective Αυτό το πείραμα προφανώς και θέλει επειγόντως αλλαγή. Τα δεδομένα του έπρεπε να είναι κανονικοποιημένα πριν γίνει όλο αυτό, αφού έτσι δεν βγαίνει κανένα νόημα. To test the hypothesis that the allocation of free allowances to countries is correlated with a set of economic and energy attributes that define each country's profile. Specifically, we aim to determine if countries with attribute profiles closer to the "average" profile receive similar levels of free allowances.

Hypothesis There exists a statistically significant correlation between the Euclidean distance of each country's attribute profile from the average profile and the Euclidean distance of each country's free allowance allocation from the average free allowance allocation. This correlation suggests that similar countries (in terms of economic and energy attributes) should receive similar levels of free allowances.

Variables

1. **Attributes vector ($\langle \vec{X} =< \vec{x_1}, \vec{x_2}, \dots \rangle$):**A vector of standardized attributes for each country i that describes its economic and energy profile.
2. **Free Allocation (Y_i):** The amount of free allowances allocated to each country i under the EU ETS.
3. **Euclidean Distance of Attributes (D_{x_i}):** he Euclidean distance of each country's attributes vector X_i from the midean country X_{mid}
4. **Euclidean Distance of Free Allowance Allocation (D_{Y_i}):** The Euclidean distance of each country's free allowance allocation Y_i from the free allowance allocation of the median country Y_{mid}

Experimental Group Most EU member countries subject to ETS during the study period (2005–2020). In particular: Austria, Belgium, Bulgaria, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovenia, Spain, Sweden. Some where excluded due to data scarcity.

3.1.3 Methodology

1. **Determine the Median Country**: Using the algorithm 1, identify the median country profile based on the attributes vectors $\vec{X}$ for all countries. This $\overrightarrow{X_{mid}}$ profile, serves as a reference point representing typical characteristics within the group.

2. **Calculate Euclidean Distances**. For every country i, calculate the Euclidean distance D_{x_i} between $\vec{x_i}$ and $\overrightarrow{X_{mid}}$ and the Euclidean distance D_{Y_i} between its free allowance allocation Y_i and the $\overrightarrow{Y_{mid}}$ free allowance allocation of the median country.

$$D_{x_i} = \sqrt{\sum_{j=1}^{n} (x_{i,j} - x_{mid,j})^2} \tag{3.1}$$

$$D_{Y_i} = |Y_i - Y_{mid}| \tag{3.2}$$

3. **Perform Linear Regrration analysis**. Conduct linear regression with $\overrightarrow{D_x}$ as the independent variable and $\overrightarrow{D_Y}$ as the dependent variable.

4. Get the evaluation metrics of the Regression. r^2 and p-value.

Algorithm 1: FIND MEDIAN COUNTRY (Ρεαλιστικά αυτό δε λέει τίποτα, αλλά πρόσφατα κάποιο PAPER εγραφε τόσο και πιο αυτιστικά έναν αλγόειθμο, οπότε αποφάσισα να το κάνω και εγώ)

Result: The median Country
Input: The Attributes $\vec{X}$

Initialize rank accumulation vector R with $R(c) = 0$ for each country c.
for *each attribute* A_i *in* $\vec{X}$ **do**
  Sort countries c by A_i, assigning ranks $r(c, A_i)$ from 1 to $|C|$.
end
for *each country* c **do**
  Update cumulative rank: $R(c) \leftarrow R(c) + r(c, A_i)$
end
Sort countries by $R(c)$ in ascending order. Define the median country c_{median} as:

$$c_{\text{median}} = \text{sorted}(R) \left[\frac{|C|}{2} \right]$$

Output c_{median} to find its $\overrightarrow{X_{mid}}$.

3.1.4 Data Collection

The data used are presented in this table, but can also be found on the Appendix more descriptively.

Table 3.1: List of Indicators along with the Allocation Principles of [2] (Zhou & Wang 2016)

Indicators	Principle	Data Source
Population	Fairness	https://data.worldbank.org/indicator/SP.POP.TOTL
GDP per capita	Fairness	https://data.worldbank.org/indicator/NY.GDP.PCAP.CD
Inflation	Fairness	https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG
Agriculture	Fairness	http://wdi.worldbank.org/table/4.2#
Industry	Fairness	http://wdi.worldbank.org/table/4.2#
Manufacturing	Fairness	http://wdi.worldbank.org/table/4.2#
Total Energy Supply	Fairness	https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_s/
Energy Intensity	Economic Efficiency	https://ec.europa.eu/eurostat/databrowser/view/NRG_IND_EI
Verified Emissions	Fairness	https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

3.1.5 Justification

This expweriment aims to show that the structure of countries and their industries does indeed resemble ... Each of these attributes was selected to represent either the fairness or economic efficiency principles, which form the basis of a fair and effective emissions trading system under the EU ETS. By combining demographic, economic, and energy indicators, this analysis ensures a holistic assessment of allocation fairness, while considering the distinct economic and emissions profiles of each country.

3.1.6 Experiment Results & Analysis

Εδώ θέλει μία λίστα με όλα τα r τετράγγωνο και τα π-values ώστε να βγει πως όντως έχει νόημα να πάμε στο επόμενο πείραμα. Ίσως και μερικά διαγράμματα, αλλά πολύ το κούρασα.

3.2 Clustering Analysis

3.2.1 Cluster Experiment Design

Building on Experiment 1's insights, clustering analysis is applied to group EU countries based on their economic and energy profiles, allowing us to assess if the EU ETS allocation aligns with principles of fairness and efficiency. By exploring clusters, we aim to uncover patterns in free allocation and determine whether these patterns reflect fair distribution across different economic and energy contexts.

Objective This experiment aims to identify natural clusters of EU countries based on economic and energy-related attributes and to examine the extent to which these clusters and individual at-

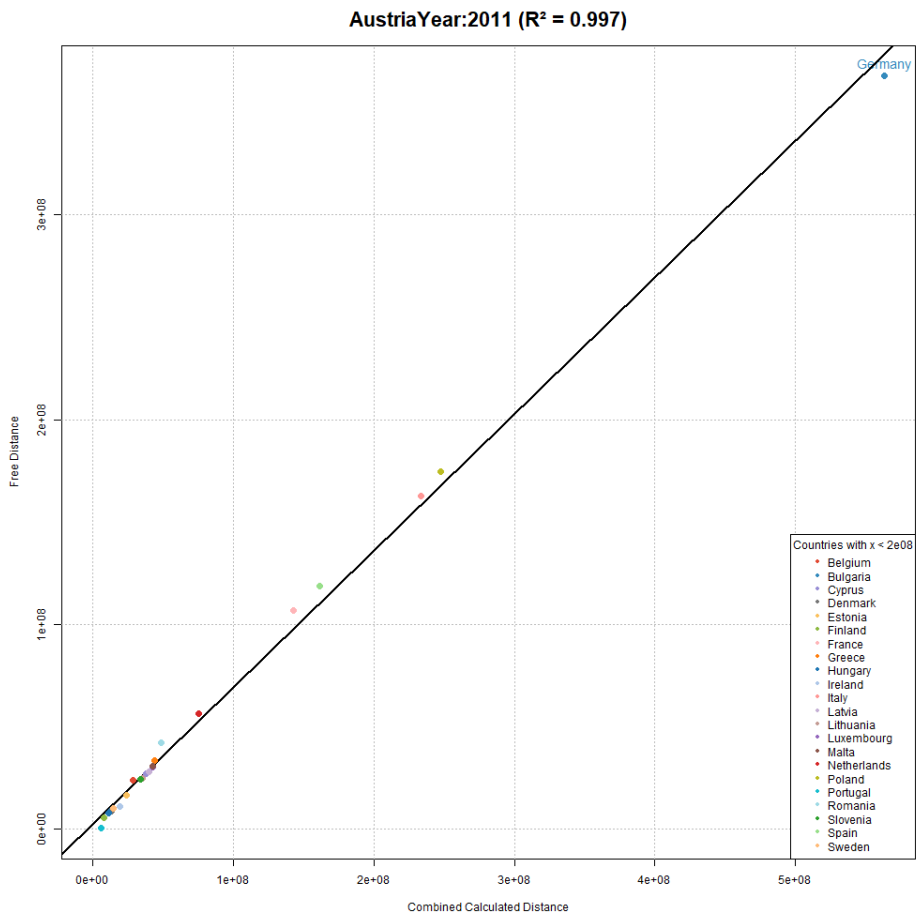

Figure 3.1: D_{x_i} with respect to D_Y, midean country Austria 2011

tributes can interpret the free allocation of emission allowances. A secondary objective is to test each attribute's individual power in explaining the variance in free allocation across countries.

Hypothesis Countries with similar economic and energy profiles, as defined by clustering, should exhibit similar levels of free allocation. Furthermore, single attributes, such as GDP per capita or verified emissions, might be hightly related to the free allocation. Which attributes do so, will privide insight into the relationship between individual attributes and free allocation distribution.

Variables

1. **Attributes vector ($\langle \vec{X} =< \vec{x_1}, \vec{x_2}, \dots \rangle$)**: A vector containing attributes (e.g., population, GDP per capita, sectoral GDP composition, energy intensity) representing each country's economic and energy profile.

2. **Free Allocation (Y_i)**: The amount of free allowances allocated to each country i under the EU ETS.

3. **Individual Attribute (A)**: Single attributes from the Country Attributes vector (e.g., GDP per capita, total energy supply) tested for their explanatory power on free allocation.

4. **Cluster Assignement (C)**: : The assigned cluster for each country.

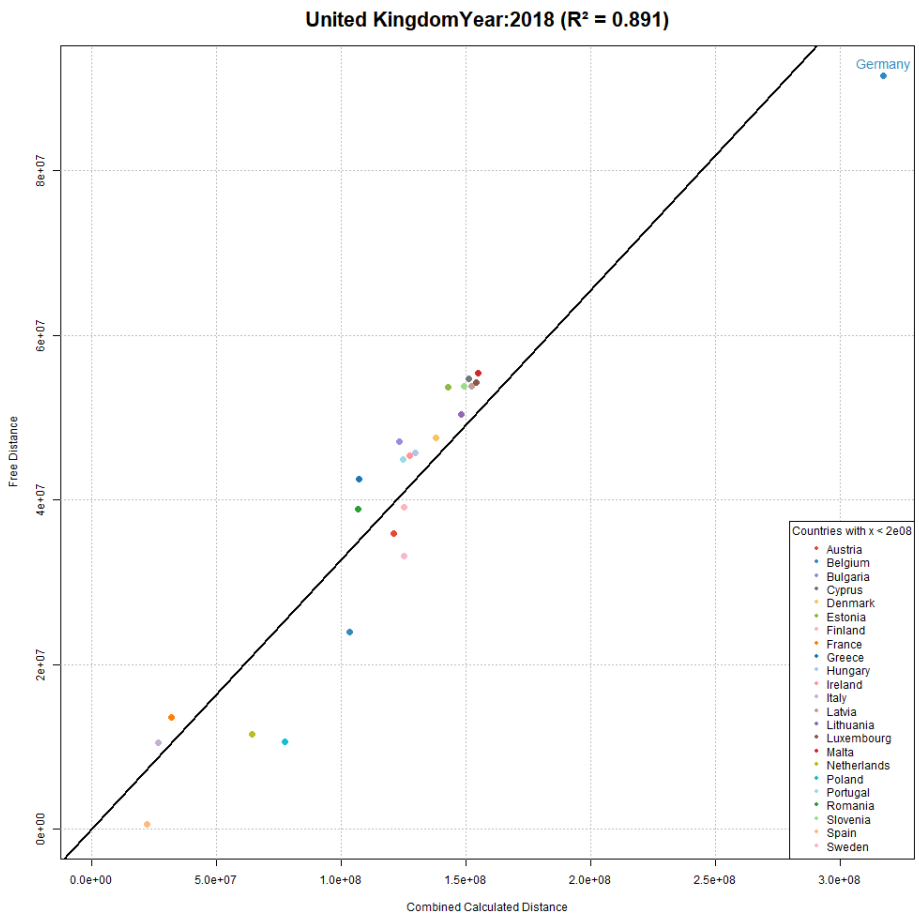

Figure 3.2: D_{x_i} with respect to D_Y, midean country United Kingdom 2018

3.2.2 Methodology

Normalization

Find the best cluster number

k-means

single attribute linear regression inside clusters

3.2.3 Results and Interpretation

Εδώ πολλά διαγράμματα, άλλα μέσα στον χρόνο, άλλα όχι κλπ.

3.2.4 Clustering extended

Principal Component Analysis

Correlation Matrix section 2 cest23 [1] (Dimos et al., 2023)

Chapter 4

Model of Allowance Allocation as an Optimization Problem

4.1 Introduction

In this chapter, we move from analyzing the fairness and efficiency of current allocation practices to proposing an optimized allocation model. Based on the findings from Chapter 3, this model aims to balance the principles of fairness (as represented by clusters and individual attributes) with economic efficiency. By framing the allocation as an optimization problem, we seek to provide a framework that maximizes fairness and compliance with economic and environmental goals under the EU ETS.

We believe that the previous experiments have shown that viewing the free allocation of permits as a country-centric problem is not entirely unjustifiable. This is why we will attempt to combine this approach with the sector-based approach in an optimization problem, which aims to balance efficiency and fairness. The efficiency will be encapsulated in the objective function of the problem. On the other hand, the fairness will be denoted by the constraints of the problem. Our goal is to provide a versatile tool to analyze allocation principles with a simple allocation mechanism.

At the end of this chapter, we will include different formulations of the problem, to simulate different fairness principles.

4.2 Mathematical Formulation

Variables

1. **Percentage of free Allocation** $v_{i,j,t}$: The percentage of the Free Allocation which is to be allocated to the country i, the sector j and year t. The year t will be omitted most of the time, and will primarily be used as $t-1$ to refer to the previous year.
2. **Sectors** $j \in S$. We denote j as the sectors and S the set of all the sectors.
3. **Countries** $i \in C$. We denote i the country and C the set of all countries.
4. $GDP_{i,j}$. The Gross Domestic Product produced in country i by sector j.
5. **Verified Emission** $e_{i,j}$. We denote the verified emissions of sector j in country i, as $e_{i,j}$.
6. **Purchase Power Standards multiplier (PPS_i).** This is a multiplier is similar to the PPP (used by the ICP (International Comparison Program)), and is used to convert euros into purchasing power.
7. v_i. The aggregate percentage of free Allocation given to the country i.
8. v_j. The aggregate percentage of free Allocation given to the sector j.
9. **Multiplier** α_k. These multipliers will have other meanings depending on their definition and will be used to encapsulate fairness/efficiency principles.

Formal Definition

$$maximize \sum_{i \in C} \sum_{j \in S} v_{i,j} \cdot \frac{GDP_{i,j}}{e_{i,j}} \cdot PPS_i \tag{4.1}$$

$$s.t. \sum_{i \in C} \sum_{j \in S} = 1 \tag{4.2}$$

Additional/Optional Constraints

$$v_i = \sum_{i \in S} v_{i,j} \tag{4.3}$$

$$v_j = \sum_{j \in C} v_{i,j} \tag{4.4}$$

$$\alpha_1 \cdot v_{i,t-1} \leq v_{i,t} \leq \alpha_2 \cdot v_{i,t-1} \tag{4.5}$$

$$\alpha_3 \cdot v_{j,t-1} \leq v_{j,t} \leq \alpha_4 \cdot v_{j,t-1} \tag{4.6}$$

$$v_i \simeq \frac{\text{Population}_i}{\text{Total Population}} \tag{4.7}$$

$$v_{i,j} \simeq \frac{\text{GDP}_{i,j}}{GDP_i} \tag{4.8}$$

$$\alpha_1 = \min\left(0.8, \frac{\overline{GDP}}{\overline{GDP_i}}\right) \tag{4.9}$$

$$\alpha_1 = \min\left(1.2, \frac{\overline{GDP}}{\overline{GDP_i}}\right) \vdots \tag{4.10}$$

Explanation of the constraints

4.3 Solution & Methodology

Algorithm Selection Linear, Convex, MIP with regard to the constraint complexity.

Data Inputs As in section 3

4.4 Example Runs

4.5 Results & Explanation of differences and comparison with historical data

Chapter 5

Simulations / Comparison with another model

5.1 Definition of another model from the bibliography

5.2 Formulation/solving tools

5.3 Connection between the models

5.4 Comparison between results

Chapter 6

Conclusions and Policy Implications (πολύ φιλόδοξο :P)

Chapter 7

Future Work

Chapter 8

Random Ideas for chapters

8.1 Literature Review

πριν το chapter 1

8.2 Methodology

Ισως να μπουν όλες οι τεχνικές και όλα τα μαθηματικά εργαλεία σε ένα σημείο για να είναι όλα τους καλά οργανωμένα και να μην γίνονται αναφορές σε αυτά σε τυχαία σημεία της διπλωματικής. Ίσως πριν την παράγραφο 3, αμέσως μετά την ουσιαστική εισαγωγή.

8.3 Theoretical Foundations

Ισως κάποια εισαγωγικά για κάποιον που δεν είναι σχετικός με τα μαθηματικα εργαλεία; Τρολλιές λέω τώρα, το ξέρω.

8.4 Sensitivity Analysis and Robustness of the Models

Μου αρέσει να έχω όνειρα στη ζωή μου. Κάποια τα βλέπω από μικρό παιδί και συνεχίζω να τα βλέπω και να διανθίζονται...

8.5 Stakeholder Analysis and Social Acceptance

Εδώ θα μπορούσε να μπει το κομμάτι του Mulin αλλά από άλλες σκοπιές. Ήδη οι χώρες δεν είναι οι stakeholders πρεος τους οποίους το σύστημα προσπαθεί να είναι δίκαιο, οπότε γιατί όχι και άλλους.

Chapter 9

Appendix

9.1 Data selection

Energy Intensity measures the amount of energy used per unit of GDP, indicating a country's efficiency in energy use relative to economic output. Lower energy intensity reflects greater energy efficiency, suggesting a reduced need for free allowances. This attribute helps ensure that allowance distribution aligns with the goal of incentivizing efficient energy usage and reducing overall emissions across the EU.

- Principle: Economic Efficiency
- File: nrg_ind_ei_linear.csv
- Source: `https://ec.europa.eu/eurostat/databrowser/view/NRG_IND_EI__custom_5726612/default/table?lang=en`
- Field in question on nrg_bal is "EI_GDP_PPS"
- Country: All countries
- Year: 1996 - 2021
- Unit: KGOE_TEUR_PPS

Verified Emissions directly quantify a country's annual emissions and represent its environmental impact. Including verified emissions allows for an accurate reflection of each country's contribution to total emissions, thus supporting a fair allocation of allowances. By aligning the allowances with verified emissions, the EU ETS ensures that countries receive allocations proportional to their emissions levels, thereby supporting a fair distribution that respects actual emissions data.

- Principle: Fairness
- File: Historical emissions_data.csv
- Source: `https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1`
- Country: All countries
- Year: 1990 - 2021
- Unit: K tons of Co2 equivalent

Historical Emissions

- File: Historical emissions_data.csv
- Source: https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1
- Country: All countries
- Year: 1990 - 2021
- Unit: K tons of Co2 equivalent

GPD per capita reflects a country's economic wealth and ability to fund emissions reductions independently. Including this metric in the analysis acknowledges that wealthier countries have more financial capacity to invest in green technologies, potentially reducing their need for free allowances. Incorporating GDP per capita aligns with a fairness-based approach, as it considers vertical equity—ensuring that countries with lower economic resources are not disproportionately burdened in the transition to greener economies.

- Principle: Fairness
- File: GDP_per_capita_1960_2021.csv
- Source: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD
- Data: GDP per capita (current US$)
- Country: All countries
- Year: 1960 - 2021
- Unit: US$

Inflation affects purchasing power and the overall cost of living, influencing a country's economic stability and its ability to absorb additional costs associated with emissions trading. High inflation rates may signal economic vulnerabilities, making it harder for countries to manage fluctuations in emissions trading markets. By including inflation as an attribute, the analysis respects the fairness principle by accounting for economic conditions that might otherwise disadvantage certain countries.

- Principle: Fairness
- File: Inflation_1960_2021.csv
- Source: https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG
- Data: Inflation, consumer prices (annual
- Country: All countries
- Year: 1960 - 2021
- Unit:

Population is a fundamental indicator of a country's size and resource needs. Larger populations imply greater demand for energy and, subsequently, higher emissions, suggesting that allocation should consider the number of inhabitants to ensure an equitable distribution of allowances. Population-based allocation also aligns with fairness principles, as it supports the idea that countries with more people should have proportionate access to resources under a shared system.

- Principle: Fairness
- File: API_SP.POP.TOTL_DS2_en_csv_v2_4701113.csv
- Source: `https://data.worldbank.org/indicator/SP.POP.TOTL`
- Country: All countries
- Year: 1960 - 2021
- Unit: Persons

Total Energy Supply represents a country's energy consumption needs, which correlates with its emissions output. Countries with higher energy supply requirements typically have higher emissions, necessitating a proportional allocation to meet their demand. This attribute respects the fairness principle, as it aligns the allowances with the actual energy demand of each country, thereby supporting a distribution that reflects each country's energy usage and emissions potential.

- Principle: Fairness
- File: nrg_bal_s__custom_4143365_linear.csv
- Source: Eurostat
- Data tree : All data -> Environment and energy -> Energy -> Energy statistics -> quantities Energy statistics -> quantities, annual data -> Energy balances
- Data name on Eurostat: Simplified energy balances
- Data: Energy balance
- Country: All countries
- Year: 1990 - 2020
- Unit: Thousand tonnes of oil equivalent
- nrg_bal codes:
- Primary production -> PPRD
- Imports -> IMP
- Exports -> EXP
- Gross Available Energy -> GAE
- Total energy supply -> NRGSUP
- Available for final consumption -> AFC

Sectoral GDP Composition (Agriculture, Industry, Manufacturing). The economic structure of a country, represented by the composition of its sectoral GDP, directly impacts its emissions profile. Countries with a higher reliance on industry or manufacturing tend to have greater emissions intensity, which should be considered in allocation. Analyzing sectoral GDP composition supports a fair allocation by recognizing that countries with emissions-intensive economies face distinct challenges compared to those with service-based economies. This attribute thus enhances vertical equity and ensures allowances are distributed in line with each country's economic activity type.

- Principle: Fairness

9.2 Collective data

Bibliography

[1] S. Dimos, D. Fotakis, A. Mathioudaki, and K. Papadopoulos, "Fair and efficient allocation of eu emission allowances," *Global NEST International Conference on Environmental Science & Technology*, 2023. [Online]. Available: https://cms.gnest.org/sites/default/files/Proceedings/cest2023_00077/cest2023_00077.pdf

[2] P. Zhou and M. Wang, "Carbon dioxide emissions allocation: A review," *Ecological Economics*, vol. 125, p. 47–59, May 2016.