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Greenhouse Gases Emissions Reductions through the Development of Renewable Energy Production in Catalonia

Exploratory data analysis demonstrating the necessity of expanding renewable energy production to achieve greenhouse gas emission reduction goals and forecasting based on current energy consumption

Annotation

This study explores the role of renewable energy in reducing GHG emissions in Catalonia. It aims to determine whether increasing renewable energy production contributes to emission reductions, quantify the amount of renewable energy needed to meet the 2030 goal, assess whether emissions could be reduced through consumption reduction alone, quantify the amount of renewable energy needed to meet the 2030 goal taking into account current consumption. By analyzing historical data and developing predictive models, this research provides insights into the feasibility of achieving emission reduction targets and informs energy policy and investment decisions. The findings contribute to the broader discussion on energy transition strategies and highlight the necessity of scaling up renewable energy production to meet climate objectives.

Introduction

In recent years, Spain has been addressing an intense ecological transition agenda, which is proving to be a lever for the modernization of the economy, the creation of sustainable employment, the strengthening of competitiveness, and the reduction of external energy dependence, as indicated by reports from various international organizations and national-level indicators.

This transition is an opportunity for the development of rural areas, the improvement of people's health and the environment, and social justice. As data from recent years show, Spain is particularly well positioned in terms of renewable resources, as well as human, technological, and industrial capacities to successfully address this transformation.

The National Integrated Energy and Climate Plan (PNIEC) serves as the national strategic orientation tool that integrates energy and climate policy with a 2030 time horizon, in accordance with national and European regulations.

In this sense, the implementation of public policies included in the PNIEC allows Spain to aspire to be one of the winning countries in terms of energy transition, as advances up to this point have demonstrated. It is a transformation in which the Spanish economy stands to gain significantly in terms of competitiveness, materializing in the form of prosperity, energy security, industrial job creation, innovation, technological development, and reduction of energy poverty.

Furthermore, the presence of this opportunity for clean, affordable, and secure energy generation from a supply perspective, coupled with regulations on self-consumption, allows for the installation of productive activities near renewable generation areas. This brings the benefits of energy transition in the form of high-quality industrial employment closer to the territories where the consequences of renewable development are most immediately felt.

In line with European energy and climate policies, the Government of Spain has developed the Strategic Framework for Energy and Climate. One of the key components of this Strategic Framework is Law 7/2021 of May 20 on climate change and energy transition, which establishes the regulatory framework to ensure Spain's compliance with the Paris Agreement goals, facilitate the decarbonization of the economy, and promote a sustainable development model. Additionally, this law includes planning instruments to address energy transition, such as the national integrated energy and climate plans and the Long-Term Decarbonization Strategy to 2050, thereby consolidating the energy planning tools included in Regulation (EU) 2018/1999 of December 11 on the Governance of the Energy Union and Climate Action into national legislation.

The first national energy and climate plan, covering the period 2021-2030, was adopted in 2020, and since then there has been an increase in climate ambition at the European level, reflected in the European Climate Law and the "Objective 55" and "REPowerEU" plans.

As a result, and in accordance with Article 14.2 of Regulation (EU) 2018/1999 of December 11, the update of the National Integrated Energy and Climate Plan for 2023-2030 has been developed (in line with the provisions of Law 21/2013 of December 9 on environmental assessment, the document has undergone a strategic environmental assessment), including objectives consistent with the emissions reduction adopted at the European level, resulting in the following outcomes for 2030:

		Resultados en 2030
Generales	Reducción de emisiones de GEI respecto a 1990	32%
	Reducción de emisiones de GEI respecto a 2005 – Sectores ETS	-70%
	Reducción de emisiones de GEI respecto a 2005 – Sectores difusos	-42%
	Porcentaje de renovables en la generación eléctrica	81%
	Número de vehículos eléctricos	5,5 millones
	Número de viviendas rehabilitadas	1.377.000
	Potencia total y renovable del mix energético	Total: 214 GW Ren.: 160 GW
	Porcentaje renovables sobre energía final	48%
	Eficiencia Energética. Reducción de consumo de energía primaria	-39,5%
	Eficiencia Energética Reducción de consumo de energía final	-43%
	Dependencia energética	50%
Transporte	Reducción intensidad de emisiones de GEI transporte	16,3%
	Porcentaje de renovables en el sector transporte	28%
	Porcentaje combinado de RFNBO[1] + Bios avanzados y biogás del Anexo IX Parte A	17,26%
Industria	Incremento anual de la cuota de energías renovables en la industria	2,14% (2021-2025) 2,97% (2026-2030)
	Porcentaje de RFNBO sobre el hidrógeno en la industria	74%
Edificación, calefacción refrigeración	Energía final procedente renovables en edificios	67,59%
	Aumento anual porcentaje renovables calefacción y refrigeración	1,42% (2021-2025) 2,36% (2026-2030)

«Plan Nacional Integrado de Energía y Clima», Gobierno de España

The following goals are highlighted as the main ones in both PINEK and in particular in Catalonia Energy Outlook 2050 (PROENCAT 2050):

- 32% reduction in greenhouse gas emissions compared to 1990
- 48% renewable energy in final energy consumption
- 43% improvement in energy efficiency in terms of final energy
- 81% renewable energy in electricity generation
- Reduction of energy dependence by up to 50%

My research unquestionably contributes to understanding all the objectives. On the other hand, for the emissions assessment, I worked with primary energy, and for the investigation of the second and third objectives, I would also need to delve into final energy, for the fourth, consider total energy production as well, and for the fifth, energy imports and exports. I focused my research on the first objective and, in the process, formulated and answered four key questions:

1. Does increasing renewable energy production contribute to reducing GHG emissions in Catalonia?
2. How much renewable energy needs to be produced in Catalonia to reduce GHG emissions by 32% compared to 1990 levels?
3. Is it possible to reduce GHG emissions in Catalonia by 32% compared to 1990 levels only through consumption reduction without increasing renewable energy production?
4. How much renewable energy needs to be produced in Catalonia to reduce GHG emissions by 32% compared to 1990 levels without reducing consumption?

Datasets

I used two dataset and the following variables in them:

Emissions_de_GEH_a_Catalunya_20250127.csv: Annual data on various pollutants by sectors, sections, classes and subclasses of the emission inventory according to the IPCC methodology from 1990 to 2022.

- **ANY:** All present years from 1990 to 2022;
- **CONTAMINANT:** Greenhouse Gases (GHG): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC, several types), perfluorocarbons (PFC, several types) and sulfur hexafluoride (SF_6). For the study, I transformed the data to get total emissions by year. For the charts in the presentation, I transformed the data to get CO_2, CH_4 and N_2O emissions separately, because

they are the biggest polluters, and combined HFC, PFC and SF_6 into «Other gases»;
- **UNITATS:** Gg, 1 Gg = 1000 tons;
- **CO2EQ:** Emissions of all gases are presented in CO_2 equivalent;
- **EMISSIO GAS**: Emissions values

SERIE-BALANC-1990-2022-web.xlsx: Energy balance of Catalonia from 1990 to 2022. The energy balance of Catalonia presents the items that describe the different operations of each energy source: production and consumption of primary energy, consumption in the transformation of electricity generation and in refineries and olefins plants, consumption specific to the energy sector, losses in transport and distribution of energy, non-energy consumption, as well as final consumption by sector.

I only interacted with primary energy, so I used primary production and primary consumption from sheets «Producció Primària» and «Consum Primària» respectively. These are pivot tables, so it was necessary to read them correctly and some transformations to get rid of the column offsets. For the study, I used only the totals, the breakdown by energy sources for the graphs in the presentation, and for them I also calculated the total production of non-renewable energy.

Units of measurement are kTOE, these are Tons of Oil Equivalent, 1 TOE is equivalent to the amount of energy released by burning one ton of crude oil, about 41.868 GJ or 11.63 MWh of energy. 1 kTOE = 1000 TOE = Thousand TOE = 1 Miles de TEP = 11.63 * 1 GWh.

- **1990-2022:** All present years from 1990 to 2022;
- **Carbó:** Coal energy;
- **Petroli:** Petrol energy;
- **Gas natural:** Gas natural energy;
- **Nuclear:** Nuclear energy;
- **Saldo intercanvis elèctrics**[1] **:** Actual electricity losses are defined as the difference between the electricity supplied to the network and the electricity released from the network to consumers;
- **Residus industrials no renovables:** Non-renewable industrial waste energy;
- **Energies renovables:** Total renewable energy production;
- **Solar**[2] **:** Solar energy, any technology that uses solar energy to produce heat or electricity;
- **Solar tèrmica**[1] **:** Solar thermal energy, technology that uses solar radiation to heat water or another heat carrier, it is used in domestic and industrial hot water supply and heating systems;
- **Solar fotovoltaica**[1] **:** Solar photovoltaic energy, technology that uses solar radiation to heat water or another heat carrier, it is used in domestic and industrial hot water supply and heating systems;

- **Solar termoelèctrica**[1]**:** Thermoelectric solar energy, technology based on the use of solar panels (photovoltaic cells) to directly convert sunlight into electricity, it is the most common method of producing electricity from solar energy;
- **Eòlica:** Wind power energy;
- **Hidràulica:** Hydraulics energy;
- **Biomassa forestal i agrària**[2]**:** Forest and agricultural biomass;
- **Biomassa agrària, animal i forestal**[1] **:** Agricultural, animal and forest biomass;
- **Residus renovables:** Renewable waste energy;
- **Biogàs:** Biogas, gas obtained by hydrogen or methane fermentation of biomass;
- **Biocarburants:** Biofuels, fuel from plant or animal raw materials, from the waste products of organisms or organic industrial waste;
- **Calor ambient:** It is energy that is naturally present in the air, water or ground and can be used for heating or cooling.

[1] — only for energy consumption
[2] — only for energy production

Thus, I have three dataframes for comfortable work in Power BI with data broken down by categories and all the listed fields, and one concated dataframe with selected fields for analysis:

```
Index: 33 entries, 1990 to 2022
Data columns (total 11 columns):
 #   Column                           Non-Null Count  Dtype  
---  ------                           --------------  -----  
 0   Non-renewable energy production  33 non-null     float64
 1   Renewable energy production      33 non-null     float64
 2   Total production                 33 non-null     float64
 3   Non-renewable energy consumption 33 non-null     float64
 4   Renewable energy consumption     33 non-null     float64
 5   Total consumption                33 non-null     float64
 6   CO2                              33 non-null     float64
 7   CH4                              33 non-null     float64
 8   N2O                              33 non-null     float64
 9   Other gases                      33 non-null     float64
 10  Total emissions                  33 non-null     float64
```

Final dataframe, S10_EDA.ipynb

Methods

1. Data Preparation

Objective: Collect, clean, and prepare data for analysis

- **Data Collection:**
  - Sources: Open data of Catalonia and the Catalan Energy Institute (look at References)
  - File formats: CSV, Excel

- **Preprocessing:**
  - Loading data into pandas
  - Skipping unnecessary rows, handling merged cells
  - Converting data types and setting indices
  - Stack: Python, openpyxl, pandas, numpy

- **Final dataset formation:**
  - Merging tables
  - Stack: Python, openpyxl, pandas, numpy

2. Hypothesis 1: Does increasing renewable energy production contribute to reducing GHG emissions in Catalonia?

Objective: Statistically test the relationship between renewable energy production and emissions

- **Investigated relationship:**
  - Total Emissions vs. Renewable Energy Production

- **Correlation analysis:**
  - Calculating the Pearson correlation coefficient
  - Stack: Python, pandas, numpy, seaborn

- **Regression analysis:**
  - Building a linear regression model (linregress)
  - Calculating coefficient significance (p-value) and standart error
  - Stack: Python, pandas, numpy, scipy.stats

- **Visualization**
    - Scatterplot with regression line, heatmap, line chart
    - Stack: Power BI, Python, matplotlib, seaborn

3. Hypothesis 2: How much renewable energy needs to be produced in Catalonia to reduce GHG emissions by 32% compared to 1990 levels?

Objective: Predict the level of renewable energy production required to meet the emissions reduction target

- **Regression analysis:**
    - Solving the regression equation for the target emission level
    - Stack: Python, pandas, numpy, scipy.stats

- **Visualization**
    - Line plots with historical data and forecast point
    - Stack: Python, pandas, numpy, matplotlib, seaborn

4. Hypothesis 3: Is it possible to reduce GHG emissions in Catalonia by 32% compared to 1990 levels only through consumption reduction without increasing renewable energy production?

Objective: Assess whether emissions can be reduced to the target level without increasing renewable energy production

- **Investigated relationship:**
    - Total Emissions vs. Total Consumption

- **Regression analysis:**
    - Building a linear regression model (linregress)
    - Calculating the Pearson correlation coefficient, coefficient significance (p-value) and standart error
    - Solving the regression equation for the target emission level
    - Stack: Python, pandas, numpy, scipy.stats

- **Visualization**
    - Line plots with historical data and forecast point
    - Stack: Python, pandas, numpy, matplotlib, seaborn

5. **Hypothesis 4: How much renewable energy needs to be produced in Catalonia to reduce GHG emissions by 32% compared to 1990 levels without reducing consumption?**

   Objective: Determine the necessary level of renewable energy production without consumption reduction

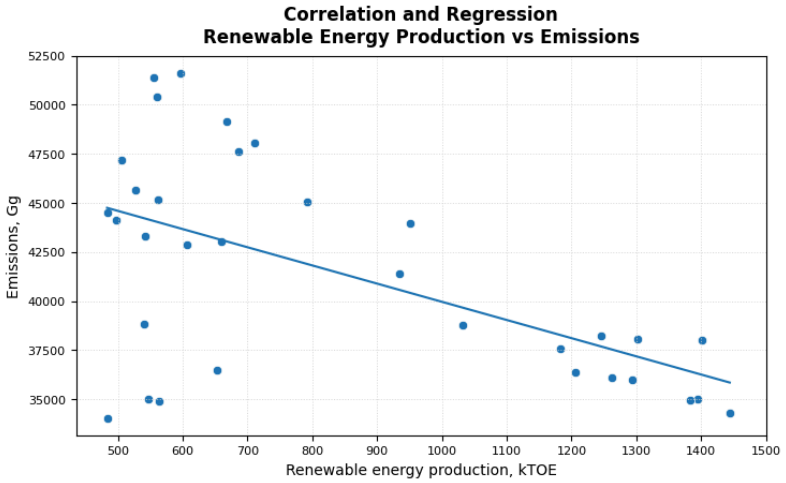
   - **Investigated relationship:**
     - Total Emissions vs. Total Consumption and Renewable Energy Production

   - **Regression analysis:**
     - Building a linear regression model (LinearRegression)
     - Calculating the Pearson correlation coefficient, coefficient significance (p-value) and standart error, checking multicollinearity
     - Solving the regression equation for the target emission level
     - Stack: Python, pandas, numpy, scipy.stats, statsmodels.api, sklearn.linear_model, statsmodels.stats.outliers_influence

   - **Visualization**
     - 3D plots with historical data, forecast surface and forecast point
     - Stack: Python, pandas, numpy, matplotlib, mpl_toolkits.mplot3d

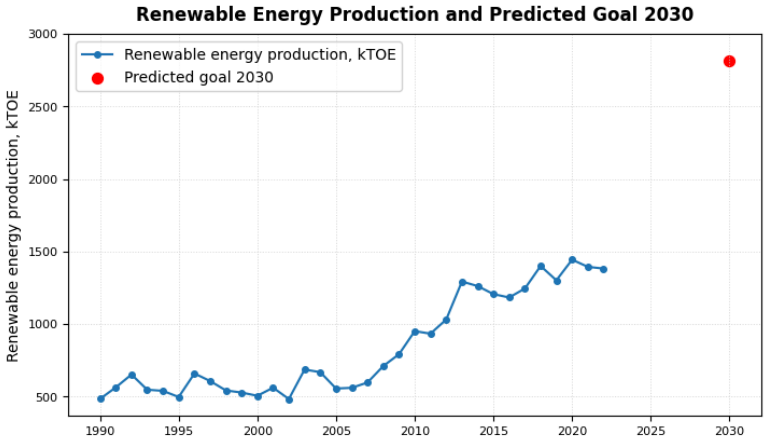
Results

1. **Hypothesis 1: Does increasing renewable energy production contribute to reducing GHG emissions in Catalonia?**



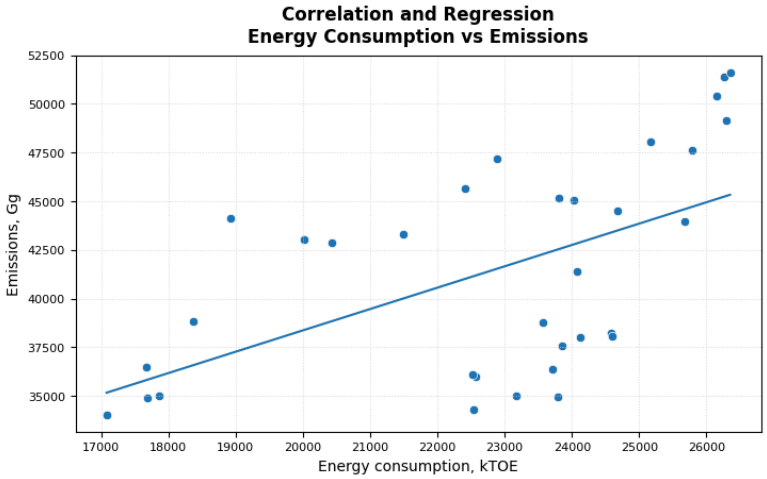

```
equation: y = -9.26x + 49225.32

slope: -9.26 ± 2.37
intercept: 49225.32

correlation: -0.57487
p-value: 0.00047

Yes, the dependence is significant
```

2. Hypothesis 2: How much renewable energy needs to be produced in Catalonia to reduce GHG emissions by 32% compared to 1990 levels?



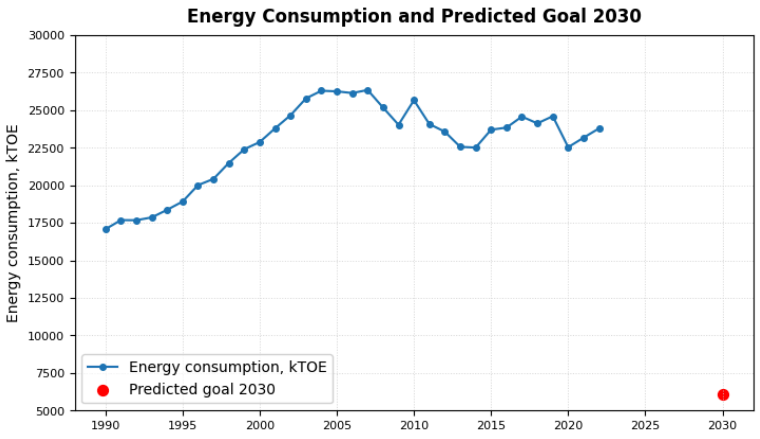

```
To reduce emissions by 32% compared to 1990 levels, renewable energy production needs to increase to: 2815.20
```

3. Hypothesis 3: Is it possible to reduce GHG emissions in Catalonia by 32% compared to 1990 levels only through consumption reduction without increasing renewable energy production?




```
equation: y = 1.10x + 16458.06

slope: 1.10 ± 0.30
intercept: 16458.06

correlation: 0.55467
p-value: 0.00081

Yes, the dependence is significant
```

```
To reduce emissions by 32% compared to 1990 levels, energy consumption would need to be reduced to: 6113.07
```



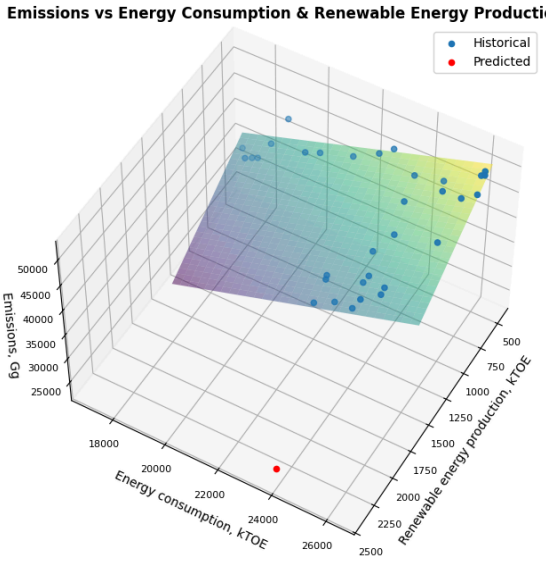
4. Hypothesis 4: How much renewable energy needs to be produced in Catalonia to reduce GHG emissions by 32% compared to 1990 levels without reducing consumption?

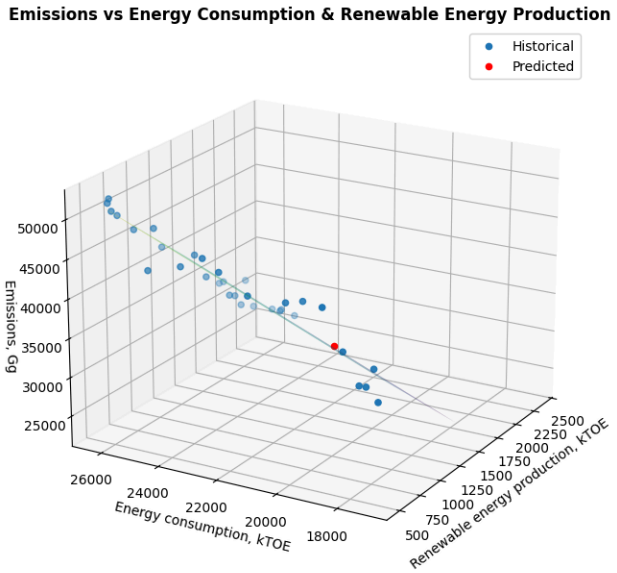
```
equation: y = −12.91x1 + 1.55x2 + 16918.61

intercept (beta_0): 16918.6109
coef of Renewable energy production (beta_1): −12.9108
coef of Consumption (beta_2): 1.5523
correlation: 0.89664
```

```
To reduce emissions by 32% compared to 1990
levels without reducing consumption, renewable
energy production needs to increase to: 2377.61
```

	Variable	VIF
0	const	69.561114
1	Renewable energy production	1.090719
2	Total consumption	1.090719

```
                            OLS Regression Results
==============================================================================
Dep. Variable:        Total emissions   R-squared:                       0.897
Model:                            OLS   Adj. R-squared:                  0.890
Method:                 Least Squares   F-statistic:                     130.1
Date:                Sun, 09 Feb 2025   Prob (F-statistic):           1.64e-15
Time:                        21:53:35   Log-Likelihood:                -293.22
No. Observations:                  33   AIC:                             592.4
Df Residuals:                      30   BIC:                             596.9
Df Model:                           2
Covariance Type:            nonrobust
================================================================================================
                                   coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------------------------
const                        1.692e+04   2662.125      6.355      0.000    1.15e+04    2.24e+04
Renewable energy production   -12.9108      0.987    -13.075      0.000     -14.927     -10.894
Total consumption              1.5523      0.121     12.819      0.000       1.305       1.800
==============================================================================
Omnibus:                        1.529   Durbin-Watson:                   1.117
Prob(Omnibus):                  0.465   Jarque-Bera (JB):                0.552
Skew:                          -0.077   Prob(JB):                        0.759
Kurtosis:                       3.615   Cond. No.                     1.92e+05
```





Discussion

The results confirm that increasing renewable energy production contributes to reducing GHG emissions in Catalonia, aligning with global research on decarbonization strategies. The analysis quantifies the renewable energy required to achieve a 32% reduction in emissions from 1990 levels, reinforcing the necessity of expanding clean energy infrastructure. The findings also indicate that consumption reduction alone is insufficient to meet the target, emphasizing the need for a dual approach combining efficiency measures and renewable energy growth. These conclusions support policy frameworks advocating for accelerated investment in renewables. Future research could explore sector-specific impacts, the role of energy storage, and the integration of emerging technologies to enhance emission reductions.

Conclusion

Catalonia has set ambitious climate goals, aiming for a 32% reduction in GHG emissions by 2030 and a full transition to renewable energy by 2050. This study demonstrates that achieving these targets is possible through a combined strategy of increasing renewable energy production and optimizing energy consumption. Continued investment in renewables and innovation in energy efficiency will be crucial in ensuring Catalonia meets its environmental commitments.

References

1) Dades obertes Catalunya. (2025, January 29). *Emissions de GEH a Catalunya*. https://analisi.transparenciacatalunya.cat/Medi-Ambient/Emissions-de-GEH-a-Catalunya/7xn6-46kz

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