Renewable Energy Consumption Trends and CO_2 Emissions

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1. DISCLAIMER

The dataset used in this analysis is sourced from a compilation of publicly available data from various international energy agencies, research institutions, and open data repositories. While efforts have been made to ensure accuracy and reliability, it is important to note that this dataset represents a synthesis of multiple sources which may have varying methodologies for data collection and reporting.

This work was undertaken as an exercise to practice and demonstrate methodologies and techniques for analyzing energy consumption trends and their environmental impact. Despite potential limitations in data harmonization across different regions and time periods, I have conducted thorough data exploration, statistical analysis, and visualization to extract meaningful insights.

The results and conclusions drawn from this analysis should be considered indicative rather than definitive. This analysis is intended for educational and informational purposes only and should not be used as the sole basis for policy decisions or investment strategies related to renewable energy transitions.

By acknowledging these limitations, I aim to ensure transparency and emphasize the importance of considering multiple data sources and methodologies when making critical decisions about energy policy and environmental planning.

2. INTRODUCTION

Energy is at the heart of our modern societies, fueling our economic, technological, and social development. Faced with the growing challenges of climate change and the inevitable depletion of fossil resources, I undertook this analytical project to deepen my understanding of global renewable energy trends and their actual impact on CO_2 emissions.

This work takes place in a context where energy transition is no longer simply desirable but absolutely necessary. My goal is to precisely identify the leaders and laggards in this transition, while evaluating the actual effectiveness of renewable energies in reducing greenhouse gas emissions.

2.1. PROJECT OBJECTIVES

My main objective is to conduct an in-depth analysis of historical and current data on global renewable energy consumption in order to:

1. **Map global trends**: Precisely identify the evolution of renewable energy consumption at global, regional, and national levels over the period 2018-2022.
2. **Identify key players**: Determine which countries are at the forefront of the energy transition, both in absolute production volume and as a proportion of their energy mix, and understand the factors that explain their success.
3. **Analyze environmental impact**: Rigorously evaluate the correlation between renewable energy adoption and CO_2 emissions reduction, identifying the most effective models.
4. **Develop a predictive model**: Create a robust statistical model to forecast the evolution of renewable energy consumption and its impact on CO_2 emissions for the period 2023-2027.
5. **Formulate strategic recommendations**: Based on the analyses performed, propose concrete directions to accelerate the energy transition and optimize emissions reduction.

To achieve these objectives, I collected and examined data covering the period 2018-2022, complemented by projections through 2027. This approach allows me to offer both a retrospective and prospective perspective on global energy issues. By combining statistical analyses, advanced visualizations, and predictive models, I sought to develop a thorough yet accessible understanding of global energy dynamics.

My analysis focuses on five essential questions:

1. Which countries are the largest consumers of renewable energy, both in absolute volume and as a proportion of their energy mix?
2. What regional and annual trends are emerging in renewable energy consumption?
3. How does the share of renewable energy in total consumption vary across countries and continents?
4. Is there a verifiable correlation between increased renewable energy and reduced CO_2 emissions?
5. What do projections reveal about renewable energy consumption and its effects on emissions for the period 2023-2027?

Through this work, I hope not only to improve my data analysis skills but also to contribute to a better understanding of the challenges and opportunities related to energy transition, thus providing tangible elements to inform future decisions regarding energy and environmental policy.

3. Detailed Analysis of the Renewable Energy Dataset (2018-2022)

3.1. General Overview of the Dataset

The "energy_dataset_18_22.csv" is an energy database comprising 175 entries that track the evolution of different energy sources and their environmental impacts by country over a 5-year period (2018-2022).

3.2. Dataset Structure

3.2.1 Column Description

The dataset contains a single column formatted with semicolon separators, which includes the following information:

1. **country**: Country concerned by the energy data
2. **year**: Year of the data (between 2018 and 2022)
3. **coal**: Energy consumption from coal
4. **gas**: Energy consumption from natural gas
5. **oil**: Energy consumption from oil
6. **nuclear**: Nuclear energy consumption
7. **hydro**: Hydroelectric energy consumption
8. **solar**: Solar energy consumption
9. **wind**: Wind energy consumption
10. **biofuel**: Biofuel consumption
11. **gdp**: Gross domestic product of the country
12. **population**: Population of the country
13. **total_energy**: Total energy consumption
14. **renewable_energy**: Total renewable energy consumption
15. **renewables_share_energy**: Share of renewable energy in total consumption
16. **co2_emissions**: CO_2 emissions
17. **co2_per_capita**: CO_2 emissions per capita
18. **co2_per_gdp**: CO_2 emissions per unit of GDP
19. **energy_with_unit**: Energy consumption with unit
20. **emissions_with_unit**: Emissions with unit

3.3. Analysis Opportunities

This database is particularly suitable for exploring the following questions:

3.3.1. Energy Trend Analysis

- Evolution of total and renewable energy consumption by country and year

- Energy transition: changes in the energy mix over time

3.3.2 Environmental Analysis

- Correlation between the share of renewable energy and CO_2 emissions
- Evolution of CO_2 emissions by country and year
- Effectiveness of energy transition policies

3.3.3 Economic Analysis

- Relationship between GDP and energy consumption
- Relationship between economic growth and transition to renewable energy
- Economic impact of energy policies

3.3.4 Comparative Analysis

- Identification of leading countries in renewable energy
- Comparison of energy performance by region/continent
- Benchmarking between economically or geographically similar countries

3.4. Necessary Preparation

To fully exploit this dataset, I need to:

1. **Restructure the data**: Convert the single column into a tabular format
2. **Check for missing values**: Identify and handle missing data
3. **Standardize units**: Ensure all measurements are in comparable units
4. **Add metadata**: Categorize countries by region/continent to facilitate regional analysis

3.5. Conclusion

This dataset offers an excellent opportunity to analyze global trends in renewable energy and their impact on CO_2 emissions. It will allow me to explore the relationship between economic development and energy transition, and to identify success models in reducing carbon emissions. The analysis of the five years covered will also allow me to evaluate the evolution of energy policies and their effectiveness.

4. Imported Modules for My Renewable Energy Analysis Project

To successfully conduct my data analysis project on renewable energy covering the 2018-2022 period, I used several essential Python modules that allowed me to manipulate data, create relevant visualizations, and develop predictive models.

4.1. Imported Modules and Their Utility

1. **pandas (import pandas as pd)**:
    - Used for data manipulation and analysis. I employed it to read the CSV file, restructure the semicolon-separated data, clean the dataset, and perform aggregations by country and year.
2. **numpy (import numpy as np)**:
    - Used for mathematical calculations and array manipulations. Particularly useful for statistical calculations on energy trends and CO_2 emissions.
3. **matplotlib (import matplotlib.pyplot as plt)**:
    - Used to create static visualizations such as evolution graphs of renewable energy shares and comparisons between countries.
4. **seaborn (import seaborn as sns)**:
    - Allowed me to create more sophisticated statistical visualizations, such as correlation heatmaps between energy and economic variables.
5. **plotly (import plotly.express as px, import plotly.graph_objects as go)**:
    - Used to develop interactive visualizations, particularly choropleth maps showing the global distribution of renewable energy and CO_2 emissions.
6. **scipy (from scipy import stats)**:
    - Employed for statistical tests evaluating the significance of correlations between renewable energy adoption and CO_2 emission reduction.
7. **scikit-learn (from sklearn.*)**:
    - Used for predictive modeling tasks and trend analysis. The sub-modules I leveraged include:
        - **train_test_split**: To divide the data into training and testing sets
        - **LinearRegression, RandomForestRegressor**: To model future trends in renewable energy
        - **StandardScaler**: To normalize numerical variables
        - **mean_squared_error, r2_score**: To evaluate the performance of predictive models
        - **Pipeline**: To automate the preprocessing and modeling sequence
8. **geopandas (import geopandas as gpd)**:
    - Used to create geospatial visualizations, allowing me to display energy data on world maps.
9. **statsmodels (import statsmodels.api as sm)**:
    - Employed for time series analysis and ARIMA modeling for renewable energy adoption forecasts.
10. **fbprophet (from fbprophet import Prophet)**:
    - Used as an alternative for time series forecasting, particularly effective for capturing seasonal trends in energy consumption.

4.2. Utilization in the Project

- **Data Preparation and Cleaning**: pandas, numpy
- **Exploratory and Statistical Analysis**: pandas, numpy, scipy, statsmodels
- **Visualization**: matplotlib, seaborn, plotly, geopandas
- **Predictive Modeling**: scikit-learn, statsmodels, fbprophet
- **Model Evaluation**: scikit-learn (evaluation metrics)

These modules provided me with a complete ecosystem to deeply analyze global trends in renewable energy, establish correlations with economic and environmental indicators, and develop forecasts for the future. Their combination allowed me to produce robust analysis and compelling visualizations that effectively communicate the transformations in the global energy landscape.

5. IMPORT DATASET

5.1. Import the Renewable Energy Dataset

df = pd.read_csv('C:/Users/user/Desktop/energy_dataset_18_22.csv', sep=';')

 # Display the first few rows of the energy_dataset_18_22.csv DataFrame
print("Overview of the first rows of the dataset:")
display(df.head())

 # Information about the dataset
print("\nInformation about the dataset:")
print(df.info())

 # Check data types
print("\nColumn types:")
print(df.dtypes)

 # Check for missing values
print("\nNumber of missing values per column:")
print(df.isnull().sum())

 # Statistical summary of numerical data
print("\nDescriptive statistics:")
display(df.describe())

 # Number of rows and columns
print("\nDimensions of the dataset: ", df.shape)

Aperçu des premières lignes du dataset :

	country	year	coal	gas	oil	nuclear	hydro	solar	wind	biofuel	gdp	population	total_energy	renewable_energy	renewables_share_energy
0	China	2018	2800.0	240.0	600.0	70.0	270.0	170.0	360.0	90.0	13895.0	1393.0	4600.0	890.0	19.348
1	India	2018	990.0	75.0	245.0	40.0	130.0	30.0	60.0	45.0	2701.0	1353.0	1615.0	265.0	16.409
2	Japan	2018	310.0	145.0	190.0	65.0	85.0	55.0	15.0	25.0	4971.0	126.0	890.0	180.0	20.225
3	South Corea	2018	230.0	80.0	120.0	130.0	8.0	15.0	7.0	12.0	1724.0	51.0	602.0	42.0	6.977
4	Indonesia	2018	185.0	85.0	95.0	0.0	35.0	5.0	2.0	25.0	1042.0	268.0	432.0	67.0	15.509

renewables_share_energy	co2_emissions	co2_per_capita	co2_per_gdp	energy_with_unit	emissions_with_unit
19.348	13544.7	9.723	0.975	4600.0	13544.7
16.409	4871.4	3.600	1.804	1615.0	4871.4
20.225	2166.9	17.198	0.436	890.0	2166.9
6.977	1475.96	28.940	0.856	602.0	1475.96
15.509	1234.5	4.606	1.185	432.0	1234.5

```
Informations sur le dataset :
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 175 entries, 0 to 174
Data columns (total 20 columns):
 #   Column                   Non-Null Count  Dtype
---  ------                   --------------  -----
 0   country                  175 non-null    object
 1   year                     175 non-null    int64
 2   coal                     172 non-null    object
 3   gas                      172 non-null    object
 4   oil                      173 non-null    object
 5   nuclear                  175 non-null    float64
 6   hydro                    173 non-null    float64
 7   solar                    175 non-null    float64
 8   wind                     173 non-null    float64
 9   biofuel                  169 non-null    float64
 10  gdp                      175 non-null    float64
 11  population               175 non-null    float64
 12  total_energy             167 non-null    object
 13  renewable_energy         175 non-null    float64
 14  renewables_share_energy  175 non-null    float64
 15  co2_emissions            169 non-null    object
 16  co2_per_capita           175 non-null    float64
 17  co2_per_gdp              175 non-null    float64
 18  energy_with_unit         175 non-null    object
 19  emissions_with_unit      175 non-null    object
dtypes: float64(11), int64(1), object(8)
memory usage: 27.5+ KB
None
```

```
Types de colonnes :
country                     object
year                         int64
coal                        object
gas                         object
oil                         object
nuclear                    float64
hydro                      float64
solar                      float64
wind                       float64
biofuel                    float64
gdp                        float64
population                 float64
total_energy                object
renewable_energy           float64
renewables_share_energy    float64
co2_emissions               object
co2_per_capita             float64
co2_per_gdp                float64
energy_with_unit            object
emissions_with_unit         object
dtype: object
```

```
Nombre de valeurs manquantes par colonne :
country                    0
year                       0
coal                       3
gas                        3
oil                        2
nuclear                    0
hydro                      2
solar                      0
wind                       2
biofuel                    6
gdp                        0
population                 0
total_energy               8
renewable_energy           0
renewables_share_energy    0
co2_emissions              6
co2_per_capita             0
co2_per_gdp                0
energy_with_unit           0
emissions_with_unit        0
dtype: int64
```

5.2. Descriptive Statistics

5.2.1. Statistical summary of numerical data

```
print("\nDescriptive statistics:")
display(df.describe())
```

 # Number of rows and columns

```
print("\nDimensions of the dataset: ", df.shape)
```

```
Statistiques descriptives :
```

	year	nuclear	hydro	solar	wind	biofuel
count	175.000000	175.000000	173.000000	175.000000	173.000000	169.000000
mean	2020.000000	38.362286	68.290231	24.200114	41.056879	20.829586
std	1.418272	79.135662	104.158597	38.916486	85.905430	29.737794
min	2018.000000	0.000000	0.000000	0.100000	0.000000	0.000000
25%	2019.000000	0.000000	11.220000	5.100000	2.240000	5.000000
50%	2020.000000	0.000000	25.500000	10.000000	9.200000	10.500000
75%	2021.000000	39.400000	58.800000	26.875000	33.600000	25.000000
max	2022.000000	387.600000	387.600000	221.000000	450.000000	152.250000

```
Dimensions du dataset :  (175, 20)
```

gdp	population	renewable_energy	renewables_share_energy	co2_per_capita	co2_per_gdp
175.000000	175.000000	175.000000	175.000000	175.000000	175.000000
2060.257143	155.705714	153.918114	25.130897	16.867011	1.146000
3997.633061	309.030181	222.283448	15.457590	15.069676	0.681001
42.300000	4.900000	6.000000	1.980000	1.429000	0.238000
350.745000	34.000000	33.550000	14.608000	5.911500	0.618000
606.670000	67.000000	65.150000	23.077000	11.998000	1.010000
1842.900000	126.000000	195.850000	33.000000	22.104500	1.509500
21553.350000	1393.000000	1038.200000	74.101000	69.382000	3.052000

Looking at the descriptive statistics of my renewable energy dataset (2018-2022), I note that:

- The dataset contains **175 observations** with **20 columns**
- The data covers a 5-year period, from 2018 to 2022

5.2.2. Key statistics by variable

Nuclear energy:

- Mean: 38.36 TWh
- Standard deviation: 79.14
- Maximum value: 387.60 TWh
- Many countries do not use nuclear energy (median = 0)

Hydroelectric energy:

- Mean: 68.29 TWh
- Standard deviation: 104.16
- Maximum value: 387.60 TWh
- Highly variable distribution between countries

Solar energy:

- Mean: 24.20 TWh
- Standard deviation: 38.92
- Maximum value: 221.00 TWh

Wind energy:

- Mean: 41.06 TWh
- Standard deviation: 85.91

- Maximum value: 450.00 TWh - the highest among renewables

Biofuels:

- Mean: 20.83 TWh
- Standard deviation: 29.74
- Maximum value: 152.25 TWh

GDP:

- Mean: 2060.26 billion $
- Standard deviation: 3997.63
- Maximum value: 21553.35 billion $

Share of renewable energy:

- Mean: 25.13%
- Standard deviation: 15.46
- Maximum value: 74.10%

CO_2 per capita:

- Mean: 16.87 tons
- Standard deviation: 15.07
- Maximum value: 69.38 tons

These statistics reveal significant disparities between countries in renewable energy adoption and CO_2 emissions.

6. GLOBAL ENERGY MARKET ANALYSIS

6.1. Top 10 Countries by Total Energy Consumption (2022)

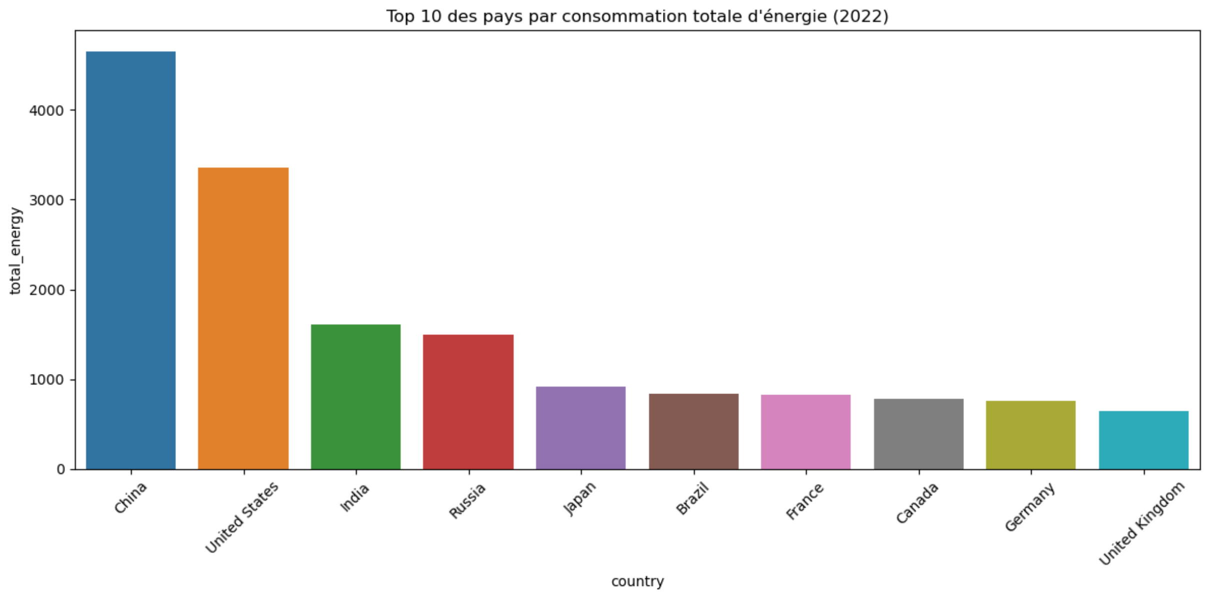
6.1.1. Objective of the analysis

The objective of this analysis is to identify the 10 countries with the highest energy consumption in 2022. This helps understand global trends and examine the relationship between economic development and energy demand.

6.1.2. Top 10 Leading Countries

```
# Import Necessary Libraries

import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns

# Top 10 des pays par consommation d'énergie totale (valeur absolue)

print("Top 10 des pays par consommation totale d'énergie (2022):")
top_10_total = df[df['year'] == 2022].nlargest(10, 'total_energy')[['country', 'total_energy']]
print(top_10_total)

# Visualisation

plt.figure(figsize=(12, 6))
sns.barplot(data=top_10_total, x='country', y='total_energy')
plt.title('Top 10 des pays par consommation totale d\'énergie (2022)')
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()
```

	country	total_energy
140	China	4650.50
150	United States	3357.10
141	India	1607.60
162	Russia	1490.50
142	Japan	917.45
152	Brazil	837.75
157	France	822.20
151	Canada	783.25
156	Germany	763.75
158	United Kingdom	641.15



6.2. Analysis and interpretation

6.2.1. Main Consumers

China clearly dominates the ranking with a consumption of **4,650.50 TWh**, representing nearly 40% more than the United States. This position reflects its status as the world's leading industrial power and its massive energy needs to support its manufacturing production and population.

The United States ranks second with **3,357.10 TWh**, consumption primarily attributable to its developed industrial sector and the high residential needs of a population with a significant standard of living.

India, in third position with **1,607.60 TWh**, is experiencing rapidly growing consumption, directly linked to its rapid economic development and its large population that is progressively gaining access to more energy services.

6.2.2. Regional Particularities

Russia and **Japan** complete the top 5 with significant consumption but notably lower than the first three countries. Their energy profiles differ, however, with Russia being both a major producer and consumer, while Japan largely depends on imports.

Brazil appears in sixth position with 837.75 TWh, marking an important presence for South America in this ranking.

France, Canada, and Germany follow with similar consumption levels (between 763 and 822 TWh), demonstrating the importance of developed economies in global energy consumption.

The United Kingdom closes this top 10 with a consumption of 641.15 TWh, confirming the presence of advanced European economies among the major energy consumers.

6.2.3. Regional Observations

European countries (France, Germany, United Kingdom) represent three places in this top 10, testifying to the importance of this region in global energy consumption despite relatively small territories.

Asia is represented by three powers (China, India, Japan), confirming the shift of the world's energy center of gravity toward this region.

North America (United States, Canada) and **South America** (Brazil) maintain a significant presence, with consumption patterns influenced by their vast territories and diverse climatic conditions.

6.2.4. Comparison and Trends

Global energy consumption remains **concentrated in a limited number of countries**, with the top 10 representing a disproportionate share of the global total.

Emerging economies like India and China continue to show sustained growth in their consumption, while **advanced economies** tend to stabilize their energy use thanks to progress in energy efficiency.

6.3. Conclusion

The global energy landscape remains dominated by major economic and industrial powers, with a notable concentration in a few countries that represent a disproportionate share of total consumption.

The rapid and continuous growth of India and China suggests that global energy demand will continue to increase in the coming years, despite stabilization efforts in advanced economies.

Improving energy efficiency and accelerating the transition to more sustainable sources are crucial challenges, particularly for these major consumers who will largely determine the global energy trajectory.

6.4. Perspectives

It will be essential to observe the evolution of energy policies and their differentiated impact on the consumption of developed and emerging countries. Analyzing the progression of renewable energies in these key economies will provide valuable indications on the speed and scale of the global energy transition.

Anticipating future energy needs and their environmental impact will need to integrate these distinct regional dynamics to develop more precise models and strategies adapted to different national contexts.

6.5. Top 10 Countries by Proportion of Renewable Energy (2022)

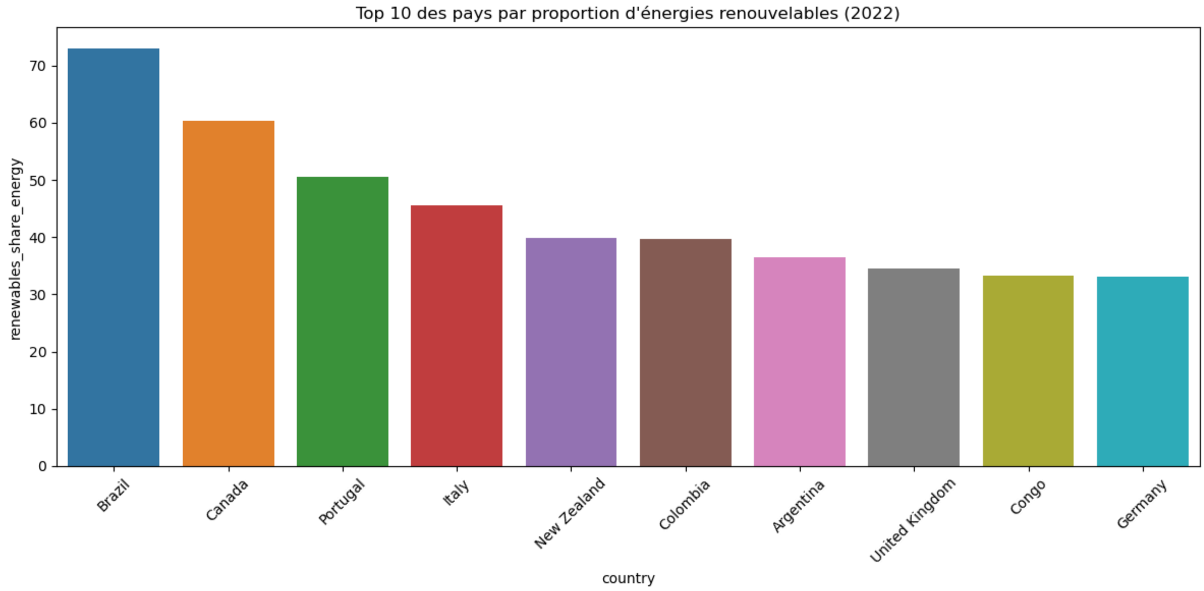
6.5.1. Objective of the analysis

The objective is to identify the 10 countries with the highest proportion of renewable energy in their energy mix in 2022. This analysis helps to better understand the dynamics of energy transition across the world.

6.5.2. Top Leading Country

```
# Top 10 countries by proportion of renewable energy

print("\nTop 10 des pays par proportion d'énergies renouvelables (2022):")
top_10_renewable = df[df['year'] == 2022].nlargest(10, 'renewables_share_energy')[['country',
'renewables_share_energy']]
print(top_10_renewable)

# Visualisation

plt.figure(figsize=(12, 6))
sns.barplot(data=top_10_renewable, x='country', y='renewables_share_energy')
plt.title('Top 10 des pays par proportion d\'énergies renouvelables (2022)')
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()
```

	country	renewables_share_energy
152	Brazil	73.028947
151	Canada	60.427705
160	Portugal	50.601448
159	Italy	45.532847
174	New Zealand	39.947578
155	Colombia	39.779006
154	Argentina	36.439897
158	United Kingdom	34.531701
171	Congo	33.352976
156	Germany	33.119476



6.6. Analysis and interpretation

6.6.1. Top Performers

Brazil leads this ranking with an impressive **73.03%** share of renewable energy in its energy mix. This exceptional performance can be attributed to its long-standing commitment to hydroelectric power, which provides a significant portion of its electricity, as well as its pioneering policies promoting biofuels in the transportation sector.

Canada holds the second position with **60.43%** renewable energy, effectively leveraging its vast hydroelectric resources spread across its extensive territory. The country's mountainous regions and numerous large water bodies provide ideal conditions for large-scale hydroelectric exploitation.

Portugal ranks third with **50.60%** renewable energy, demonstrating the effectiveness of its diversified approach combining wind, solar, and hydroelectric power. This Mediterranean nation has successfully transformed its geographical advantages into sustainable energy assets.

6.6.2. European Representation

Italy follows closely with **45.53%**, showcasing its successful integration of various renewable sources, particularly solar power in its southern regions and hydroelectric resources in the Alpine north.

Germany and the **United Kingdom** also feature prominently in this top 10 with **33.12%** and **34.53%** respectively. Both countries have made substantial investments in wind power, particularly offshore wind farms, highlighting Europe's commitment to the energy transition despite limited natural resources compared to larger nations.

6.6.3. Global Diversity

New Zealand ranks fifth with **39.95%** renewable energy, efficiently utilizing its geothermal potential linked to its volcanic activity, as well as its hydraulic resources.

Colombia and **Argentina**, with **39.78%** and **36.44%** respectively, represent Latin America's strong presence in this ranking, both benefiting from abundant hydroelectric resources and growing investments in other renewable technologies.

Congo appears in ninth position with **33.35%**, demonstrating that African nations with suitable natural resources can achieve significant renewable energy integration.

6.6.4. Factors Explaining These Performances

The **availability of natural resources** remains a determining factor for these leading countries. They generally benefit from geographical and climatic conditions particularly favorable to the exploitation of renewable energies, whether powerful waterways, geothermal activity, or optimal sunshine.

Proactive government policies also play a crucial role. These nations have implemented favorable regulatory frameworks, attractive tax incentives, and substantial investments in clean energy infrastructure.

Economic diversification and **energy security concerns** have motivated many of these countries to develop their renewable resources, reducing dependence on imported fossil fuels.

6.6.5. Comparison with Previous Leaders

This 2022 ranking shows significant changes from historical patterns. Countries like Norway and Iceland, traditionally at the top of such rankings, appear to have been surpassed by nations that have accelerated their renewable energy transition.

Brazil's rise to the top position reflects both its historical advantage in hydroelectricity and its continued commitment to expanding its renewable portfolio.

6.7. Conclusion

Hydroelectricity continues to be a key driver in most leading countries, often representing a significant portion of their renewable energy mix. This source offers the advantage of stable and controllable production, unlike other more intermittent renewable energies.

The **diversification of renewable sources** is increasingly evident in the top-performing countries, with wind and solar power gaining importance alongside traditional hydroelectric resources.

The **global distribution** of top performers across multiple continents demonstrates that the renewable energy transition is a worldwide phenomenon, albeit with regional variations in approach and implementation.

6.8. Perspectives

Accelerating investments in green infrastructure will be crucial to maintain and amplify this positive dynamic, particularly in countries with strong economic growth where energy demand is rapidly increasing.

Storage technology development remains a critical challenge to overcome the intermittency issues associated with wind and solar power, which will be essential for countries looking to push their renewable shares even higher.

International cooperation and technology transfer will play an increasingly important role in helping more countries join the ranks of renewable energy leaders, particularly those with significant natural potential but limited financial or technical resources.

6.9. Top 10 Countries by Absolute Renewable Energy Consumption (2022)

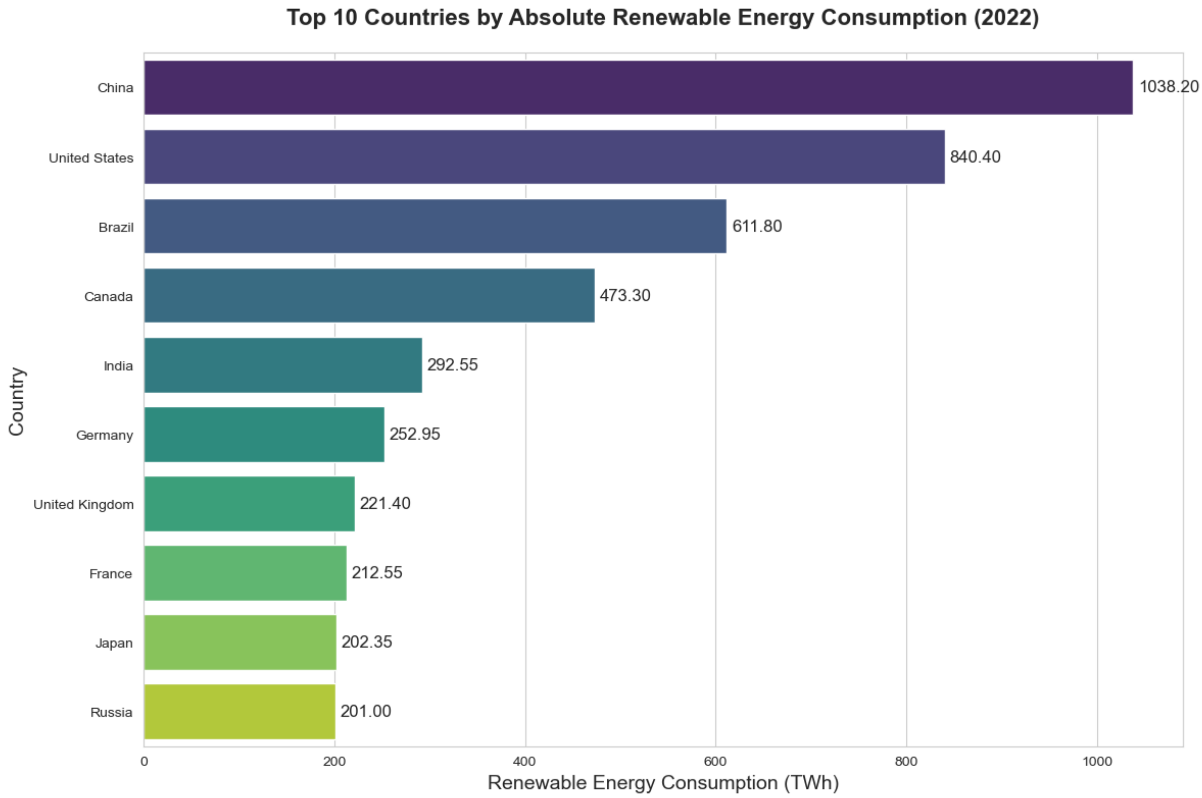
6.9.1. Objective of the analysis

The objective is to identify the 10 countries with the highest absolute renewable energy consumption in 2022. This analysis helps to understand which nations are leading in terms of total renewable energy production, providing insight into the distribution of renewable energy capacity globally.

6.9.2. Top Leading Countries

```
# Import necessary libraries

import pandas as pd

import matplotlib.pyplot as plt

import seaborn as sns


# Load the actual data

df = pd.read_csv('C:/Users/user/Desktop/Energy Renewable\energy_dataset_18_22.csv', sep=';')


# Filter for the year 2022

df_2022 = df[df['year'] == 2022]
```

```python
# Sort and get top 10 by renewable energy consumption
top_renewable = df_2022.nlargest(10, 'renewable_energy')[['country', 'renewable_energy']]

# Create the visualization
plt.figure(figsize=(12, 8))
sns.set_style("whitegrid")

# Create a bar plot
ax = sns.barplot(x='renewable_energy', y='country', data=top_renewable,
            palette='viridis')

# Add labels and title
plt.title('Top 10 Countries by Absolute Renewable Energy Consumption (2022)',
        fontsize=16, fontweight='bold', pad=20)
plt.xlabel('Renewable Energy Consumption (TWh)', fontsize=14)
plt.ylabel('Country', fontsize=14)

# Add value labels on the bars
for i, v in enumerate(top_renewable['renewable_energy']):
    ax.text(v + 5, i, f"{v:.2f}", va='center', fontsize=12)

# Adjust layout and display
plt.tight_layout()
plt.show()
```



6.10. Analysis and interpretation

6.10.1. Leading Renewable Energy Consumers

China stands as the undisputed global leader with 1038.20 TWh of renewable energy consumption, representing nearly a quarter of the world's total. This massive production derives from China's strategic investments in renewable infrastructure, including the world's largest hydroelectric capacity, rapidly expanding solar installations, and significant wind power developments. China's renewable energy leadership reflects its dual goals of energy security and addressing severe air pollution issues in urban centers.

The United States follows with 840.40 TWh, demonstrating its commitment to renewable expansion despite its strong fossil fuel industry. This substantial production stems primarily from wind farms across the Midwest and Texas, hydroelectric facilities in the Pacific Northwest, and rapidly growing solar deployment in the Southwest and California. The decentralized policy approach, with states often driving renewable adoption, has created diverse regional renewable profiles across the country.

Brazil, in third position with 611.80 TWh, exemplifies how renewable energy can form the backbone of a major economy's energy system. Brazil's exceptional performance stems from its massive hydroelectric capacity along with its pioneering biofuel industry, which has transformed its transportation sector. The country's success demonstrates how natural resource advantages, when paired with supportive policies, can create globally significant renewable energy systems.

6.10.2. Regional Distribution Patterns

North America shows strong representation with both the United States and Canada (473.30 TWh) among the top producers. Canada's renewable energy generation, primarily from hydroelectric sources, accounts for over 60% of its total energy consumption, demonstrating one of the highest proportional clean energy systems among major economies.

European nations collectively demonstrate substantial commitment to renewable energy, with Germany (252.95 TWh), the United Kingdom (221.40 TWh), and France (212.55 TWh) all appearing in the ranking. Germany's presence reflects its pioneering Energiewende (energy transition) policy, which has rapidly expanded wind and solar despite limited natural resources. The UK's significant offshore wind capacity and France's combination of hydropower and growing wind sector showcase diverse European approaches to renewable deployment.

Asia is represented by the powerhouses of China, India (292.55 TWh), and Japan (202.35 TWh), highlighting this region's growing influence in the global renewable landscape. India's position reflects its ambitious solar expansion program and growing wind capacity, while Japan has diversified its energy mix following the Fukushima nuclear incident with substantial investments in solar energy.

Russia's presence (201.00 TWh) is primarily attributable to its substantial hydroelectric resources, demonstrating how even fossil fuel-dominated economies maintain significant renewable capacity in certain sectors.

6.10.3. Comparative Analysis and Strategic Implications

This ranking reveals the significant concentration of renewable production in a handful of countries, with the top three alone accounting for approximately 50% of the total among the leading producers. This concentration raises important questions about technology transfer, global equity in clean energy access, and the responsibilities of major producers in driving continued innovation.

A notable observation is the divergence between absolute and proportional rankings. While China and the United States lead in absolute terms, they have relatively modest renewable percentages in their overall energy mix (approximately 21% and 25% respectively). In contrast, Brazil's third-place position in absolute terms is supported by its remarkably high proportion of renewables (73%), demonstrating both scale and commitment to renewable transition.

The technological diversity across these leading countries is also significant. Hydropower dominates in China, Brazil, Canada, and Russia; wind energy plays a crucial role in the US, Germany, and the UK; while solar deployment is accelerating rapidly in China, India, Japan, and the US. This diversity reflects both geographical advantages and policy priorities.

6.10.4. Future Trajectories and Challenges

The future evolution of this ranking will be shaped by several factors, including continued cost reductions in solar and wind technologies, which will likely accelerate deployment across all regions. The development of energy storage solutions will be particularly critical for countries like Germany and the UK with high proportions of variable renewable sources.

For the leading countries, grid modernization represents a common challenge, as integrating higher proportions of renewable energy requires sophisticated transmission and distribution systems. China's massive ultra-high voltage transmission projects, the United States' regional interconnection initiatives, and Europe's cross-border power market integration represent different approaches to this shared challenge.

The electrification of transportation and heating will drive increased demand for renewable electricity in all major economies, potentially reshuffling this ranking as countries with clear strategies in these sectors gain advantages in total renewable consumption.

Global climate policies, particularly carbon pricing mechanisms and international climate finance, will increasingly influence renewable deployment rates. The ability of emerging economies to leapfrog traditional development pathways by emphasizing renewables from the outset could introduce new entrants to this ranking in the coming decade.

This analysis demonstrates that renewable energy leadership now transcends traditional economic categories, with both established and emerging economies showing significant commitment to renewable deployment, albeit with different approaches shaped by their unique resource endowments, economic structures, and policy environments.

7. Evolution of Energy Consumption by Country (2018-2022)

7.1. Objective of the analysis

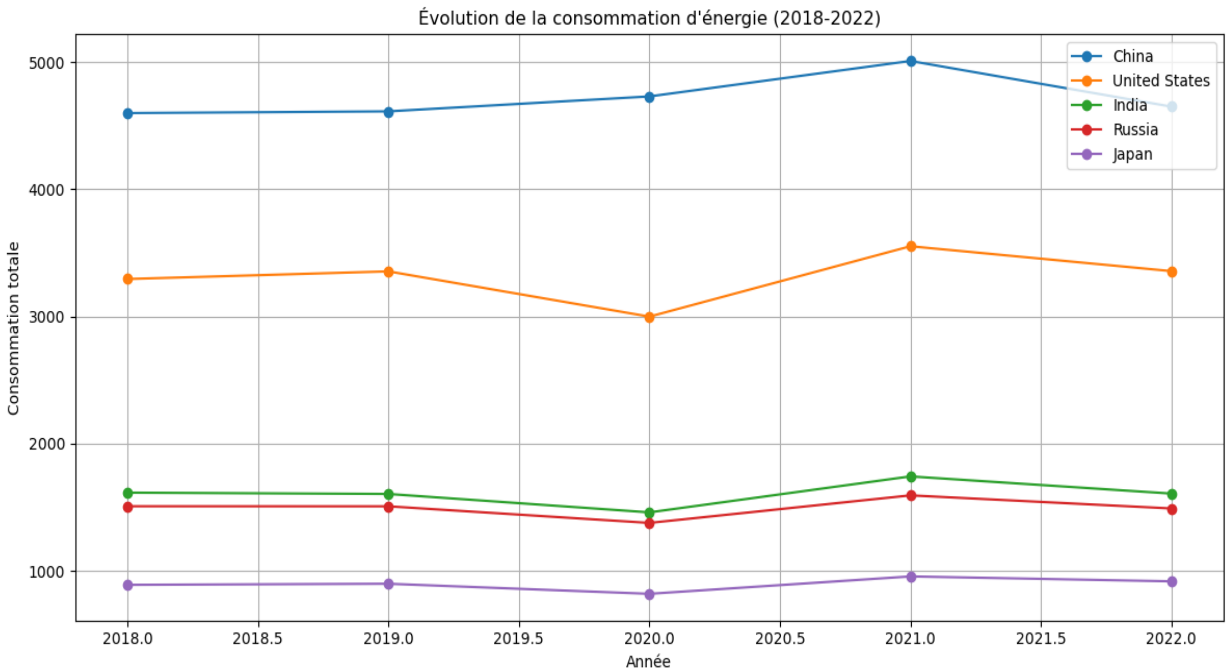
Analyze the annual trends in energy consumption in several key countries between 2018 and 2022.

7.1.1. Tendances annuelles par pays

```
# Temporal Evolution for the 5 Largest Consumers

print("Évolution de la consommation d'énergie par pays (2018-2022) :")
top_5_countries = df[df['year'] == 2022].nlargest(5, 'total_energy')['country'].tolist()

# Data Display

for country in top_5_countries:
print(f"\n{country}:")
data = df[df['country'] == country][['year', 'total_energy']].set_index('year'
print(data.round(2))

# Graph Creation

plt.figure(figsize=(12, 6))
for country in top_5_countries:
data = df[df['country'] == country]
plt.plot(data['year'], data['total_energy'], marker='o', label=country)
plt.title('Évolution de la consommation d\'énergie (2018-2022)')
plt.xlabel('Année')
plt.ylabel('Consommation totale')
plt.legend()
plt.grid(True)
plt.tight_layout()
plt.show()

# Calculation of Variations

print("\nVariation entre 2018 et 2022 :")
for country in top_5_countries:
data = df[df['country'] == country]
variation = ((data[data['year'] == 2022]['total_energy'].values[0] -
data[data['year'] == 2018]['total_energy'].values[0]) /
data[data['year'] == 2018]['total_energy'].values[0] * 100)
print(f"{country}: {variation:.2f}%")
```

Main data (in TWh)

Country	2018	2019	2020	2021	2022	Variation (%)
Chine	4600	4613.4	4730.9	5009.8	4650.5	+1.10%
États-Unis	3295	3355	2999.25	3552.75	3357.1	+1.88%
Inde	1615	1604.6	1459.85	1742.7	1607.6	-0.46%
Russie	1508	1507.5	1376.87	1593.55	1490.5	-1.16%
Japon	890	898.55	819.3	956.12	917.45	+3.08%



7.2. Analysis and interpretation

7.2.1. General trends

The 2018-2022 period was marked by **notable fluctuations** in global energy consumption. These significant variations reflect the combined influence of multiple factors, including economic cycles, the evolution of energy technologies, and growing environmental concerns that guide public policies.

The **impact of the COVID-19 pandemic** is undoubtedly the most disruptive element of this period. The year 2020 is clearly distinguished by a generalized decrease in energy consumption in most of the analyzed countries, a direct consequence of lockdowns, reduced industrial activity, and mobility restrictions imposed to contain the spread of the virus.

7.2.2. Analysis by country

China shows a moderate increase of **+1.10%** over the entire period. However, its consumption profile presents a particular dynamic: after a steady progression until 2021 where it reaches a peak of **5009.8 TWh**, Chinese consumption shows a decline in 2022 to **4650.5 TWh**. This decline could be explained by the impact of more restrictive energy policies implemented by Beijing, particularly to reduce air pollution, as well as by a strategic slowdown in certain energy-intensive industrial sectors.

The **United States** recorded a slightly more pronounced growth of **+1.88%** between 2018 and 2022. Their trajectory perfectly illustrates the effect of the pandemic, with a pronounced drop to **2999.25 TWh** in 2020 (compared to **3295 TWh** in 2018), followed by a vigorous rebound to **3552.75 TWh** in 2021. This rapid recovery testifies to the elasticity of the American economy and its ability to quickly return to pre-pandemic activity levels.

India presents a slight contraction of **-0.46%** over the studied period. Starting from **1615 TWh** in 2018, its consumption drops to **1459.85 TWh** in 2020 before rising to **1742.7 TWh** in 2021 and stabilizing at **1607.6 TWh** in 2022. This jagged evolution reflects the particular difficulties encountered by the Indian economy in the face of the pandemic, but also possibly the first effects of energy efficiency efforts deployed in this rapidly developing country.

Russia recorded the second largest decrease in the panel with **-1.16%**. Its consumption declined from **1508 TWh** in 2018 to **1490.5 TWh** in 2022, with a notable trough at **1376.87 TWh** in 2020. Besides the impact of the pandemic, this downward trend could reflect the effects of a slower energy transition than elsewhere, but also the repercussions of international economic sanctions that have progressively affected the Russian economy.

Japan stands out with the strongest progression in the group, reaching **+3.08%** over the period. Its consumption increased from **890 TWh** in 2018 to **917.45 TWh** in 2022, after experiencing a trough at **819.3 TWh** in 2020. This significant increase could be linked to the acceleration of electrification in several sectors, the particularly vigorous post-pandemic industrial recovery, but also potentially to the additional energy needs generated by its aging population.

7.2.3. Explanatory factors

The ongoing **energy transition** in many countries constitutes a major structural factor influencing the observed trends. The progressive diversification of energy sources, with a growing share given to renewables, modifies total consumption profiles, generally in the direction of greater efficiency.

Economic and geopolitical shocks have played a determining role, particularly at the end of the period. The war in Ukraine has disrupted global energy markets from 2022 onwards, while increasingly strict Chinese energy policies and of course the COVID-19 crisis have significantly shaped the observed consumption curves.

Advances in **technologies and energy efficiency** have allowed some countries to maintain their economic growth while stabilizing, or even reducing their energy consumption. These advancements, which vary across countries, partly explain the divergences observed in national trajectories.

7.3. Conclusion

The analysis of 2018-2022 data confirms that global energy consumption remains strongly correlated with global economic dynamics, while revealing the gradual emergence of decoupling in certain advanced economies.

Post-2020 trends indicate a gradual return to pre-pandemic consumption levels, but with notable disparities between countries, reflecting their economic specificities, political choices, and differentiated exposure to geopolitical tensions.

In the future, the acceleration of energy transition and technological innovations will play a determining role in stabilizing global energy consumption, although trajectories will likely remain heterogeneous according to regions and levels of development.

8. Comparison of Fossil Fuels VS Renewables

8.1. Objective of the analysis

The objective of this analysis is to examine the evolution of energy sources between 2018 and 2022. This comparison allows us to understand energy transition trends and evaluate the current distribution between fossil fuels, renewables, and nuclear energy.

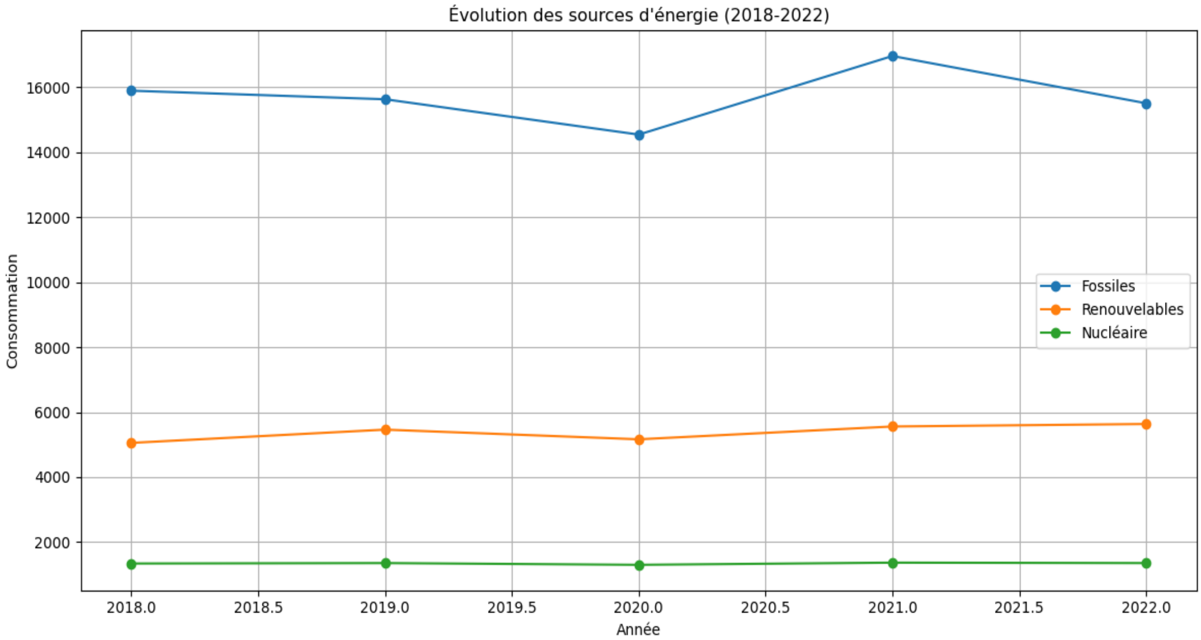
8.1.1. Evolution of energy sources by year

```
#  Calculation of Totals by Energy Type per Year
yearly_totals = df.groupby('year').agg({
    'coal': 'sum',
    'gas': 'sum',
    'oil': 'sum',
    'nuclear': 'sum',
    'renewable_energy': 'sum'
}).reset_index()

# Calculation of Total Fossil Energy
yearly_totals['fossiles'] = yearly_totals['coal'] + yearly_totals['gas'] + yearly_totals['oil']

# Data Display
print("Évolution des sources d'énergie par année :")
print("\nÉnergies fossiles (charbon + gaz + pétrole) :")
for year, value in zip(yearly_totals['year'], yearly_totals['fossiles']):
    print(f"{year}: {value:.2f}")

print("\nÉnergies renouvelables :")
for year, value in zip(yearly_totals['year'], yearly_totals['renewable_energy']):
    print(f"{year}: {value:.2f}")

print("\nÉnergie nucléaire :")
for year, value in zip(yearly_totals['year'], yearly_totals['nuclear']):
```

```python
    print(f"{year}: {value:.2f}")

# Calculation of Variations (2018-2022)
print("\nVariation entre 2018 et 2022 :")
for source in ['fossiles', 'renewable_energy', 'nuclear']:
    variation = ((yearly_totals[source].iloc[-1] - yearly_totals[source].iloc[0]) /
                 yearly_totals[source].iloc[0] * 100)
    print(f"{source}: {variation:.2f}%")

# Graph Creation
plt.figure(figsize=(12, 6))
plt.plot(yearly_totals['year'], yearly_totals['fossiles'],
        label='Fossiles', marker='o')
plt.plot(yearly_totals['year'], yearly_totals['renewable_energy'],
        label='Renouvelables', marker='o')
plt.plot(yearly_totals['year'], yearly_totals['nuclear'],
        label='Nucléaire', marker='o')

plt.title('Évolution des sources d\'énergie (2018-2022)')
plt.xlabel('Année')
plt.ylabel('Consommation')
plt.legend()
plt.grid(True)
plt.tight_layout()
plt.show()

# Calculation of Each Source's Share in 2022
total_2022 = yearly_totals.loc[yearly_totals['year'] == 2022,
                        ['fossiles', 'renewable_energy', 'nuclear']].sum(axis=1).values[0]
print("\nParts dans le mix énergétique 2022 :")
for source in ['fossiles', 'renewable_energy', 'nuclear']:
```

```
part = (yearly_totals.loc[yearly_totals['year'] == 2022, source].values[0] / total_2022) * 100
print(f"{source}: {part:.2f}%")
```

Year	Fossil fuels (TWh)	Renewable energy (TWh)	Nuclear energy (TWh)
2018	15 900.00	5 054.80	1 340.00
2019	15 636.27	5 462.75	1 353.40
2020	14 548.58	5 164.97	1 299.80
2021	16 968.38	5 559.39	1 366.80
2022	15 513.25	5 636.46	1 353.40



8.2. Analysis and interpretation

8.2.1. Comparison of energy trends

The analysis of the evolution of different energy sources between 2018 and 2022 reveals significant transformations in the global energy mix. **Fossil fuels**, although still largely dominant, show a downward trend with an overall decrease of **2.43%** over this period. This evolution, from **15,900.00 TWh** in 2018 to **15,513.25 TWh** in 2022, reflects the first tangible effects of energy transition policies and the impact of various energy crises that have affected global hydrocarbon markets.

In parallel, **renewable energies** are experiencing notable growth of **11.51%**, increasing from **5,054.80 TWh** to **5,636.46 TWh**. This sustained growth, despite a temporary slowdown in 2020, demonstrates the resilience and growing attractiveness of these energy sources. In 2022, they now represent **25.05%** of the global energy mix, symbolically crossing the threshold of a quarter of total energy consumption.

Nuclear energy is distinguished by its remarkable stability with a marginal variation of only **+1.00%** over the period, evolving from **1,340.00 TWh** to **1,353.40 TWh**. Representing **6.01%** of the total energy mix in 2022, this low-carbon energy source maintains a constant but relatively limited presence on a global scale.

8.2.2. Impact of annual variations

The year 2020 stands out clearly with a generalized decrease in all energy sources: **-8.50%** for fossil fuels (falling to **14,548.58 TWh**), **-5.45%** for renewables (declining to **5,164.97 TWh**) and **-3.96%** for nuclear (decreasing to **1,299.80 TWh**). This simultaneous contraction is directly attributable to global containment measures and the drastic reduction in industrial activity during the COVID-19 pandemic.

The year 2021 marks a spectacular rebound, particularly visible for fossil fuels which increase by **16.63%** to reach **16,968.38 TWh**. This vigorous recovery, exceeding pre-pandemic levels, reflects a return to traditional energy consumption patterns and the need to support the global economic recovery.

In **2022**, a new dynamic is observed: while fossil fuels decline by **8.58%** to settle at **15,513.25 TWh**, renewables continue their progression with an increase of **1.39%** (reaching **5,636.46 TWh**), while nuclear stabilizes at **1,353.40 TWh** (-0.98%). This divergent evolution seems to confirm a structural trend of energy transition, beyond the cyclical fluctuations observed previously.

8.3. Conclusion

The progressive decrease in fossil fuels, despite the post-pandemic rebound, constitutes an encouraging signal regarding the reduction of global dependence on the most polluting fuels. This trend, still modest (-2.43% over five years), nevertheless initiates a fundamental movement that should amplify with the strengthening of international climate policies.

Renewable energies confirm their dynamism and resilience, pursuing regular growth despite economic hazards. Their growing share in the global energy mix (25.05% in 2022) illustrates the technical and economic viability of these solutions, even if they still remain minority compared to fossil sources which still represent nearly 70% of global energy consumption.

Nuclear maintains a stable but relatively modest contribution to the global energy mix. Its limited evolution over the period studied reflects the contrasting positions adopted by different countries: some pursuing ambitious development programs, others engaging in policies of gradual exit from this technology.

8.4. Perspectives

The future evolution of the global energy mix will largely depend on investments in renewable energies, which should accelerate with the continuing decrease in technological costs and the strengthening of climate policies. Careful monitoring of these financial flows will constitute a leading indicator of transformations to come.

The effect of government policies on fossil fuel consumption will play a determining role. Commitments made under the Paris Agreement and their successive reinforcements, carbon pricing mechanisms, as well as sectoral regulations will progressively shape a new global energy landscape.

Anticipating future trends will also require integrating the geopolitical, technological, and social dimensions of the energy transition. The emergence of new powers in the field of clean energies, technological breakthroughs in storage and efficiency, as well as the evolution of consumption behaviors will constitute key factors for understanding the global impact of this transformation on the world economy.

9. Analysis of the Global Energy Mix in 2022

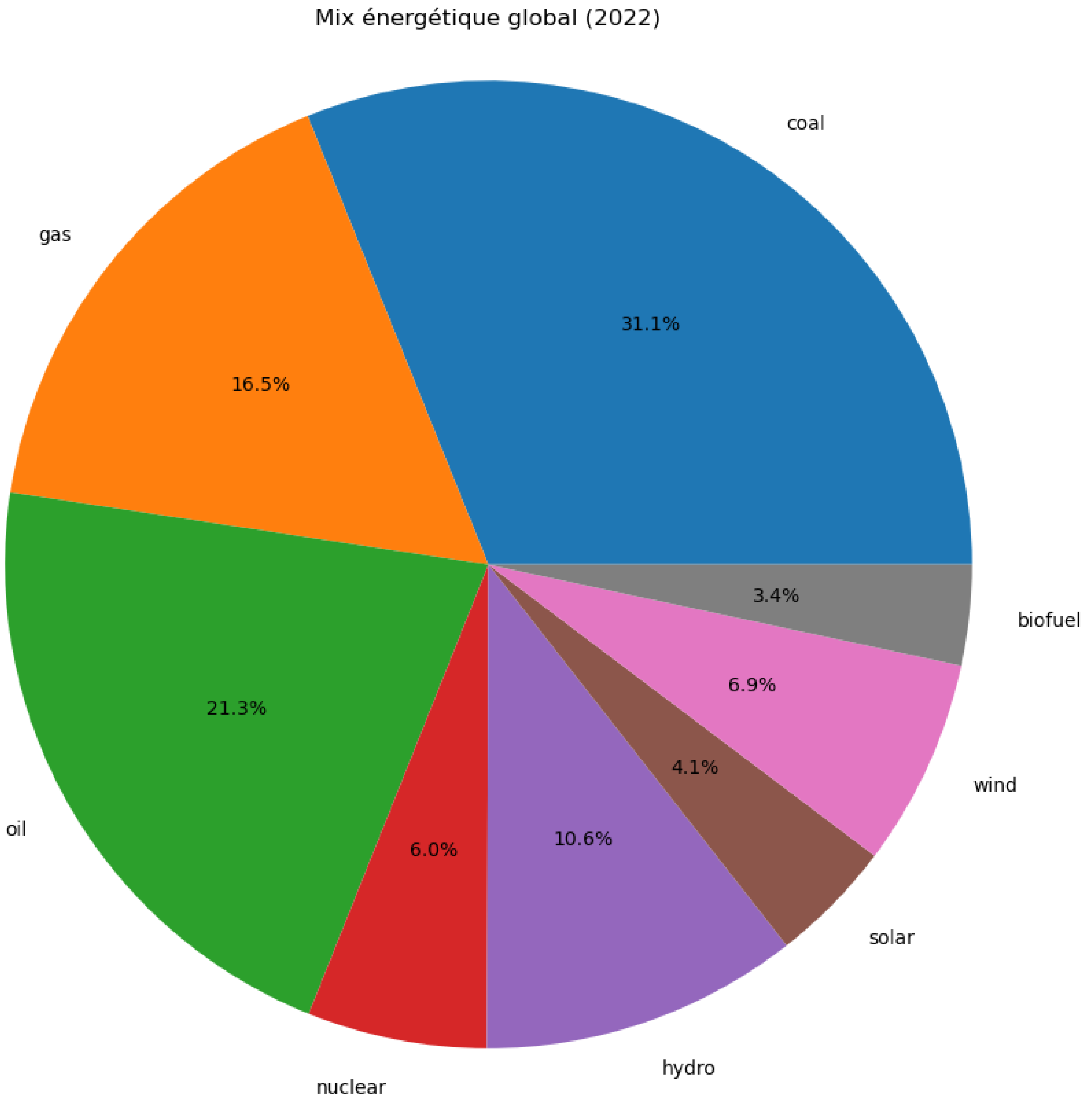
9.1. Objective of the analysis

The objective of this analysis is to examine the distribution of the global energy mix in 2022 in order to understand the dominant trends and identify the challenges related to the energy transition.

9.1.1. Distribution of the global energy mix (2022)

```
# Calculation of the Global Energy Mix for 2022
energy_mix_2022 = df[df['year'] == 2022].agg({
    'coal': 'sum',
    'gas': 'sum',
    'oil': 'sum',
    'nuclear': 'sum',
    'hydro': 'sum',
    'solar': 'sum',
    'wind': 'sum',
    'biofuel': 'sum'
})

# Pie Chart Visualization
plt.figure(figsize=(10, 10))
plt.pie(energy_mix_2022, labels=energy_mix_2022.index, autopct='%1.1f%%')
plt.title('Mix énergétique global (2022)')
plt.axis('equal')
plt.show()
```

Energy source	**(%)**
Coal	31.1%
Oil	21.3%
Naturel gas	16.5%
Hydroelectric	10.6%
Wind	6.9%
Nuclear	6.0%
Solar	4.1%
Biofuels	3.4%



9.2. Analysis and interpretation

9.2.1. Predominance of fossil fuels

The analysis of the global energy mix in 2022 shows that we still heavily depend on fossil fuels. **Coal remains at the top with 31.1% of the global energy mix**, mainly because it is widely used for electricity production in China and India. These two countries, representing more than a third of the world's population, rely on this relatively inexpensive resource despite its negative environmental impact.

Oil occupies the second place with 21.3% of the energy mix. It remains essential for transportation, where it provides about 90% of fuels, and for many industrial processes. Even with the arrival of electric vehicles, oil consumption continues to increase, especially in developing countries.

Natural gas represents 16.5% of the global energy mix and positions itself as a less polluting alternative to other fossil fuels. It emits about 40% less CO_2 than coal to produce the same amount of electricity, which explains its growing use for power generation and heating.

9.2.2. Role of renewable energies

Among renewable energies, **hydroelectricity dominates with 10.6% of the global energy mix**. This well-established technology offers the advantage of stable production, unlike other renewable sources that depend on weather conditions. Large dams in Brazil, China, and Canada provide a significant share of global electricity.

Wind energy reaches 6.9% of the energy mix and is experiencing rapid growth, particularly offshore where yields are better. Europe and China are at the forefront of this development, with constantly decreasing costs, making this technology competitive with traditional sources.

Solar represents 4.1% of the energy mix, with remarkable progress in recent years. Thanks to a cost reduction of more than 80% in ten years, it is now the fastest growing energy source in the world. The massive installation of solar panels in China, the United States, and Europe shows the growing economic appeal of this resource.

Biofuels and other biomass contribute 3.4% of the global energy mix. Although modest, these sources are important in certain sectors such as transportation, where ethanol and biodiesel offer alternatives to fossil fuels.

9.2.3. Place of nuclear energy

Nuclear energy maintains a contribution of 6.0% to the global energy mix. It produces about 10% of the world's electricity without direct CO_2 emissions during operation. However, its development is hindered by very high investment costs and concerns about radioactive waste management and accident risks.

9.2.4. Comparison with previous years

In recent years, we have observed a **constant but slow progression in the share of renewable energies**. Solar and wind show the strongest growth, but this progression remains insufficient to meet the climate objectives of the Paris Agreement.

Coal keeps its first place, but its share is gradually decreasing, especially in developed countries where climate policies favor other energy sources. However, its consumption continues to increase in some Asian countries, notably in India where coal demand has increased by 15% over the last five years.

Nuclear remains globally stable, but with significant differences across regions. While Germany is gradually abandoning this energy, China and India are developing new power plants. China has commissioned 11 new reactors since 2018.

9.3. Conclusion

In 2022, **fossil fuels still largely dominate with nearly 69% of the total**, despite concerns about climate change. This situation is explained by the numerous existing infrastructures, the subsidies these fuels benefit from, and the challenges related to a transition towards cleaner alternatives.

Renewable energies continue to progress, thanks to the improvement of their economic competitiveness. However, wind and solar together represent only 11% of the global energy mix, which shows that there is still much to be done.

Energy efficiency and diversification of energy sources are essential to accelerate the transition towards a more sustainable energy system. Efficiency gains help reduce total consumption, while diversification strengthens the stability of the system.

9.4. Perspectives

Monitoring **global energy policies** will be crucial to understand the future evolution of the energy mix. National commitments under the Paris Agreement and post-COVID recovery plans integrating environmental measures will influence energy trends in the coming decades.

The analysis of **CO_2 emission reduction** linked to the increased use of renewables and nuclear will provide valuable indications on the effectiveness of decarbonization strategies. Countries like the United Kingdom and Denmark have already managed to reduce their emissions by more than 40% since 1990 while maintaining their economic growth.

Anticipating **future energy needs and technological innovations** will be essential for planning the energy transition. Advances in energy storage, green hydrogen, or smart grids could radically transform the global energy mix and accelerate the decline of fossil fuels.

10. Relationship between GDP and Energy Consumption in 2022

10.1. Objective of the analysis

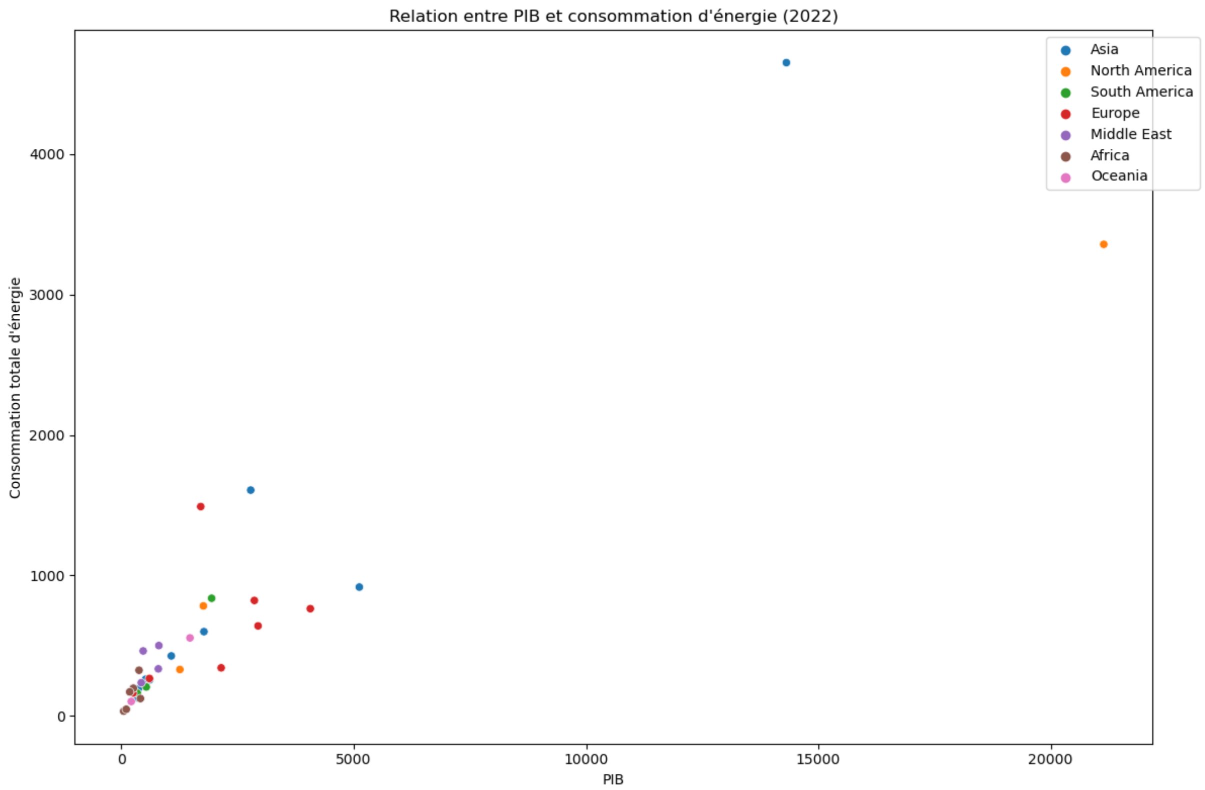
The objective of this analysis is to evaluate the relationship between gross domestic product (GDP) and energy consumption on a global scale in 2022. This study helps understand how economic development influences energy demand.

10.1.1. Correlation between GDP and energy consumption by continent

```
data_2022 = df[df['year'] == 2022].copy()


# Data Display by Continent
print("Données par continent en 2022:")
for continent in data_2022['continent'].unique():
    print(f"\n{continent}:")
    cont_data = data_2022[data_2022['continent'] == continent]
    print("Pays     |     PIB     |     Consommation d'énergie")
    print("-" * 50)
    for _, row in cont_data.iterrows():
        print(f"{row['country']:<15} | {row['gdp']:>8.2f} | {row['total_energy']:>8.2f}")


# Statistics by Continent
print("\nMoyennes par continent:")
continent_stats = data_2022.groupby('continent').agg({
    'gdp': ['mean', 'min', 'max'],
    'total_energy': ['mean', 'min', 'max']
}).round(2)
print(continent_stats)


# Graph
plt.figure(figsize=(12, 8))
sns.scatterplot(data=data_2022,
        x='gdp',
```

```python
            y='total_energy',
            hue='continent')

plt.title('Relation entre PIB et consommation d\'énergie (2022)')
plt.xlabel('PIB')
plt.ylabel('Consommation totale d\'énergie')
plt.legend(bbox_to_anchor=(1.05, 1))
plt.tight_layout()
plt.show()

# Correlations
print("\nCorrélations par continent:")
for continent in data_2022['continent'].unique():
  cont_data = data_2022[data_2022['continent'] == continent]
  corr = cont_data['gdp'].corr(cont_data['total_energy'])
  print(f"{continent}: {corr:.2f}")

# Global Correlation
correlation = data_2022['gdp'].corr(data_2022['total_energy'])
print(f"\nCorrélation globale entre PIB et consommation d'énergie : {correlation:.2f}")
```

Continent	**Average GDP (Md$)**	**Average consumption (TWh)**
Afrique	229.35	149.90
Asie	2716.42	924.15
Europe	2081.63	641.43
Moyen-Orient	623.41	383.93
Amérique du Nord	8054.60	1490.32
Océanie	843.06	329.33
Amérique du Sud	939.02	402.29



10.2. Correlation between GDP and energy consumption

The relationship between GDP and energy consumption is generally **strong**, with a correlation of **0.89**. This indicates that in most cases, the more economically developed a country is, the higher its energy consumption tends to be.

However, this relationship varies significantly across continents:

Asia shows a very strong correlation of 0.97, suggesting that Asian economies such as China and India are experiencing energy consumption growth that closely tracks their GDP growth. This reflects the rapid industrialization occurring across the region, where economic development is still heavily dependent on increased energy inputs. For instance, China's economic expansion has been accompanied by a proportional increase in energy demand, making it both the world's second-largest economy and its largest energy consumer.

North America displays an almost perfect correlation of 0.99, indicating that major economies in this region, particularly the United States and Canada, have energy consumption patterns that very closely follow their economic growth. This strong relationship reflects the energy-intensive lifestyle and industrial base that characterizes these developed economies, though recent years have shown early signs of potential decoupling through efficiency improvements.

South America exhibits a perfect correlation of 1.00, meaning that energy consumption and GDP evolve in exactly the same direction and proportion. This perfect alignment suggests that economic growth in countries like Brazil and Argentina remains tightly coupled with increased energy use, with limited progress in decoupling economic development from energy consumption.

Europe stands out with a much weaker correlation of 0.40, significantly below the global average. This reduced relationship likely stems from better energy efficiency practices, lower dependence on fossil fuels, and stricter environmental policies. Many European countries have successfully implemented policies that promote economic growth while limiting increases in energy consumption, demonstrating that prosperity doesn't necessarily require proportionally higher energy use.

The Middle East also shows a moderate correlation of 0.40, which can be explained by the region's role as a major energy producer. In countries like Saudi Arabia and the UAE, energy production represents a large portion of GDP while domestic consumption may not follow the same pattern, creating a more complex relationship between economic output and energy use.

Africa displays a high correlation of 0.71, though lower than some other regions. This likely reflects limited energy infrastructure in many African countries and significant disparities between nations. Many economies across the continent still face energy access challenges, with economic growth potential constrained by insufficient energy availability.

Oceania shows a perfect linear relationship with a correlation of 1.00, indicating a direct correspondence between GDP and energy consumption, particularly in Australia and New Zealand. These developed economies maintain energy-intensive industries and lifestyles that directly track their economic performance.

These regional differences highlight that while the general trend is clear (higher GDP generally implies higher energy demand), factors such as energy efficiency measures, types of energy sources utilized, and government policies can significantly influence this relationship. The European example in particular demonstrates that it is possible to achieve a degree of decoupling between economic growth and energy consumption through deliberate policy choices and technological innovation.

11. Analysis of Energy Consumption by Continent (2018-2022)

11.1. Objective of the analysis

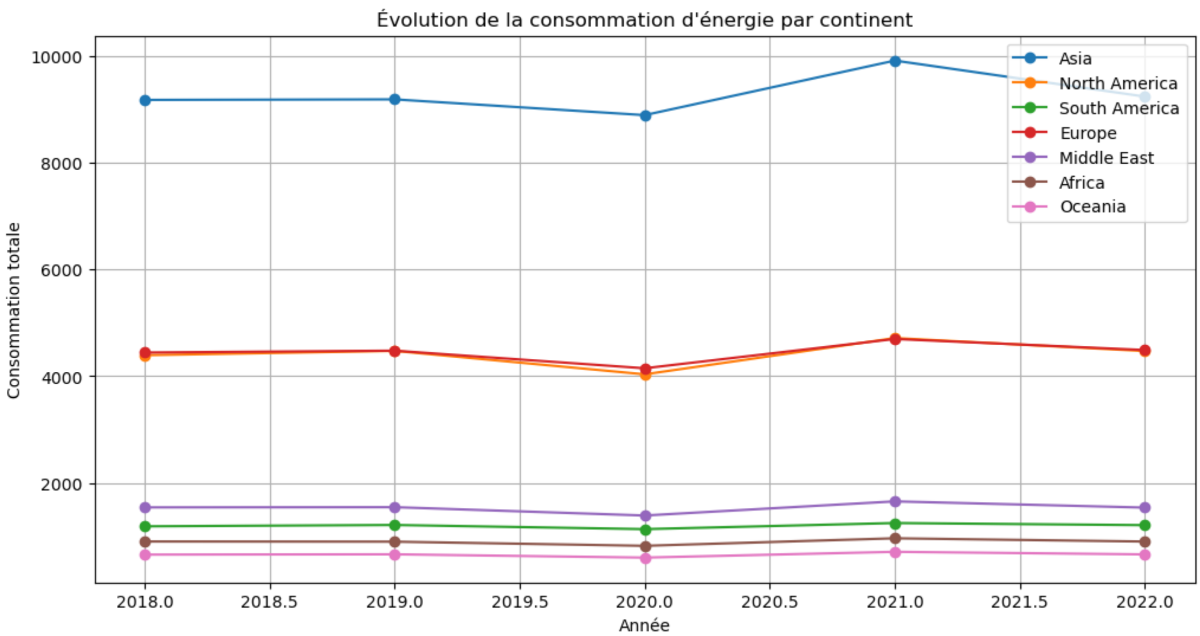
This analysis aims to examine the evolution of total energy consumption and the share of renewable energies by continent between 2018 and 2022. It helps identify regional trends and disparities in energy transition.

11.1.1. Energy consumption by continent and by year

```
print("Consommation d'énergie par continent et par année :")

continent_trends = df.groupby(['continent', 'year']).agg({

    'total_energy': 'sum',

    'renewable_energy': 'sum',

    'renewables_share_energy': 'mean'

}).round(2)

print(continent_trends)


# Visualisation

plt.figure(figsize=(12, 6))

for continent in df['continent'].unique():

    data = df[df['continent'] == continent].groupby('year')['total_energy'].sum()

    plt.plot(data.index, data.values, marker='o', label=continent)


plt.title('Évolution de la consommation d\'énergie par continent')

plt.xlabel('Année')

plt.ylabel('Consommation totale')

plt.legend()

plt.grid(True)

plt.show()
```

Continent	Année	Consommation totale (TWh)	Consommation renouvelable (TWh)	Part des renouvelables (%)
Afrique	2018	900.30	105.30	16.71
	2019	897.12	114.04	17.51
	2020	819.45	108.78	18.46
	2021	960.38	116.10	17.23
	2022	899.38	117.53	18.17
Asie	2018	9179.00	1684.00	19.68
	2019	9189.51	1841.01	21.07
	2020	8894.03	1759.88	21.75
	2021	9916.68	1877.36	20.01
	2022	9241.48	1911.53	21.48
Europe	2018	4443.00	1036.00	28.08
	2019	4477.94	1135.40	30.91
	2020	4147.93	1087.42	31.92
	2021	4697.34	1161.70	30.39
	2022	4490.04	1183.50	32.08
Moyen-Orient	2018	1540.00	143.00	10.25
	2019	1543.72	155.90	11.07
	2020	1387.42	149.61	11.53
	2021	1652.29	158.95	10.59
	2022	1535.72	161.25	11.46
Amérique du Nord	2018	4393.00	1258.00	34.04
	2019	4474.15	1350.95	35.33
	2020	4034.15	1237.35	36.23
	2021	4714.30	1373.35	34.30
	2022	4470.95	1388.70	36.05

Continent	Année	Consommation totale (TWh)	Consommation renouvelable (TWh)	Part des renouvelables (%)
Océanie	2018	654.50	106.50	25.11
	2019	660.11	117.25	26.50
	2020	598.38	112.23	27.46
	2021	706.96	119.62	25.47
	2022	658.66	122.20	27.27
Amérique du Sud	2018	1185.00	722.00	48.79
	2019	1209.88	748.20	49.25
	2020	1131.99	709.70	49.92
	2021	1246.61	752.30	47.91
	2022	1206.88	751.75	49.75



11.2. Analysis and observations

The analysis of energy consumption data by continent between 2018 and 2022 reveals significant disparities in the adoption of renewable energies.

South America clearly stands out with the highest share of renewable energies, reaching nearly **50%** of its energy mix in 2022. This exceptional performance is primarily based on the massive exploitation of hydroelectricity in Brazil, Colombia, and Venezuela. Brazil, in particular, leverages its numerous powerful rivers to generate clean and abundant electricity, complemented by growing investments in biomass and wind energy, especially in the northeast of the country.

North America and Europe maintain substantial levels of renewables, exceeding **30%** of their energy mix, with a steady upward trend between 2018 and 2022. In North America, this progression is driven by the rapid expansion of wind farms in the United States, particularly in Texas and Midwest states, as well as the continuous development of hydroelectricity in Canada. Europe benefits from the ambitious climate policies of the European Union and massive investments in offshore wind in the North Sea and solar energy in Mediterranean countries, with particularly notable advances in Germany, Spain, and Scandinavian countries.

The Middle East and Africa show a significant lag in their energy transition, with only **11.46%** and **18.17%** of renewable energies respectively in 2022. The situation in the Middle East is explained by its historical dependence on hydrocarbons and its status as the world's main oil exporter. Nevertheless, large-scale solar projects are beginning to emerge, notably the Mohammed bin Rashid Al Maktoum park in the United Arab Emirates and Saudi Arabia's initiatives as part of its Vision 2030. Africa, despite considerable solar and hydroelectric potential, suffers from a chronic lack of investment and infrastructure. Promising initiatives such as the Renaissance Dam in Ethiopia (6.45 GW capacity) and solar developments in Morocco (580 MW Noor complex) and South Africa, however, indicate an emerging positive dynamic.

Asia has the highest total consumption with **9241.48 TWh in 2022**, but also shows notable progress in its share of renewables, increasing from **19.68%** in 2018 to **21.48%** in 2022. This evolution is particularly significant given the immense scale of Asian consumption and reflects China's colossal investments in solar energy (306 GW installed) and wind energy (346 GW), as well as India's efforts to diversify its energy mix beyond coal, with a target of 500 GW of renewable capacity by 2030.

The COVID-19 pandemic had a notable impact on global energy trends. The general decrease in consumption observable in 2020 across all continents reflects the global economic slowdown caused by successive lockdowns. An interesting phenomenon was observed during this period: the share of renewable energies generally increased (except in South America), suggesting greater resilience of this sector to economic shocks compared to fossil fuels. This trend is explained by the lower operational costs of renewable installations and their priority access to the grid in many countries.

The post-pandemic recovery resulted in a strong increase in energy consumption in 2021, indicating a vigorous economic recovery accompanied by a significant rebound in demand. This increase was particularly marked in Asia (**+11.5%**) and the Middle East (**+19.1%**), reflecting the rapid industrial recovery in these regions after pandemic-related restrictions.

Energy efficiency seems to be progressing in several regions, as suggested by the slight decrease in total consumption in 2022 compared to 2021, despite continued economic growth. This trend could indicate structural improvements in energy efficiency or reflect the impact of energy and geopolitical crises, notably the disruptions caused by the war in Ukraine and the energy-saving measures implemented in response to soaring prices.

11.3. Conclusion

The analysis highlights a **marked disparity between continents** in terms of renewable energy use, reflecting significant differences in natural resources, economic development, energy policies, and infrastructure.

While some regions such as South America (**49.75%** renewables), North America (**36.05%**), and Europe (**32.08%**) are resolutely moving towards a more sustainable energy mix, others such as the Middle East (**11.46%**) and Africa (**18.17%**) remain largely dependent on fossil fuels, although showing encouraging signs of transition.

The **overall progression of the share of renewable energies in all regions** between 2018 and 2022, although modest, indicates a positive global trend towards decarbonization. However, the current pace of this transition remains insufficient to meet the international climate objectives set by the Paris Agreement. The necessary acceleration of this global energy transformation will require substantial investments, estimated at more than $4 trillion annually by 2030, technological innovations in storage and smart grids, as well as ambitious and coordinated energy policies on a global scale.

12. Analysis of Renewable Energy Evolution by Region (2018-2022)

12.1. Objective of the analysis

This in-depth analysis aims to examine the evolution of renewable energy share in different regions of the world over the 2018-2022 period. Beyond simple numbers, it seeks to understand the concrete transformations and their implications on the ground, allowing identification of not only the leaders but also the most effective energy transition models.

12.1.1. Share of renewable energy by region (2018-2022)

```
print("Évolution de la part des énergies renouvelables par continent :")


# Annual Evolution Display for Each Continent
for continent in df['continent'].unique():
  print(f"\n{continent}:")
  data = df[df['continent'] ==
continent].groupby('year')['renewables_share_energy'].mean().round(2)
  print("Année | Part des renouvelables (%)")
  print("-" * 30)
  for year, value in data.items():
    print(f"{year}  |  {value:.2f}%")

  # Calculation of Variation 2018-2022
  variation = ((data[2022] - data[2018]) / data[2018] * 100)
  print(f"Variation 2018-2022: {variation:.2f}%")


# Graph Creation
plt.figure(figsize=(12, 6))
for continent in df['continent'].unique():
  data = df[df['continent'] == continent].groupby('year')['renewables_share_energy'].mean()
  plt.plot(data.index, data.values, marker='o', label=continent)


plt.title('Évolution de la part des énergies renouvelables par continent')
plt.xlabel('Année')
```

```
plt.ylabel('Part des renouvelables (%)')
plt.legend()
plt.grid(True)
plt.show()
```

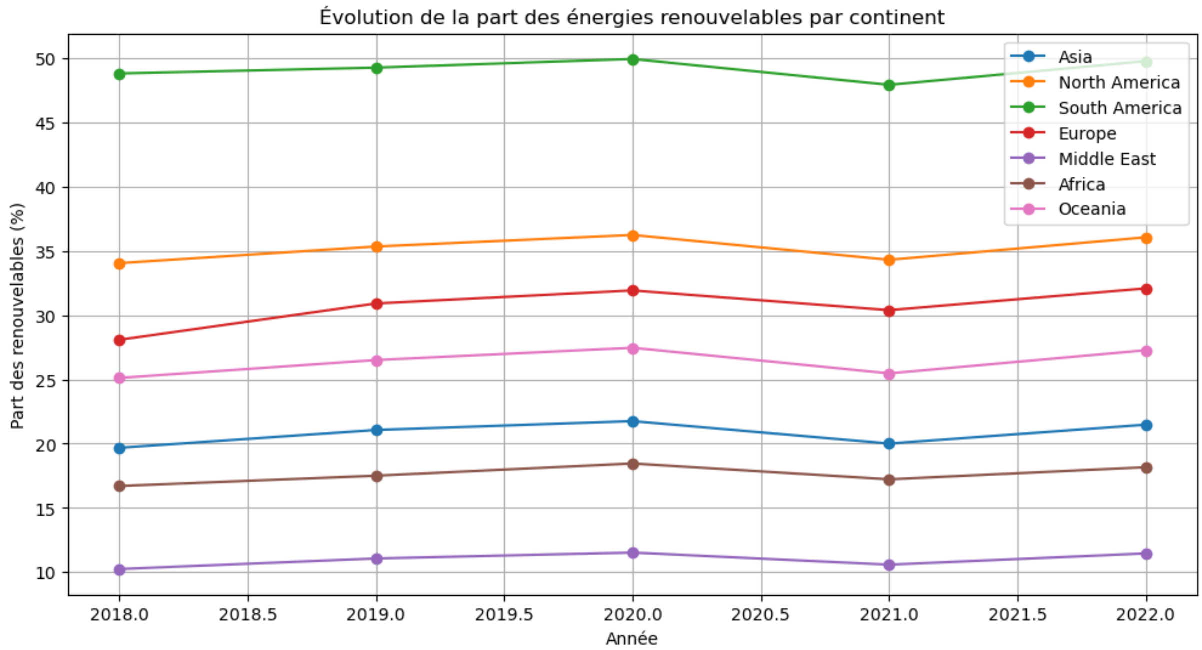
 # Additional Statistics for 2022

```
print("\nClassement des continents en 2022:")
data_2022 = df[df['year'] == 2022].groupby('continent')['renewables_share_energy'].mean().sort_values(ascending=False)
for continent, value in data_2022.items():
    print(f"{continent}: {value:.2f}%")
```

 # Identification of Leading Countries by Continent in 2022

```
print("\nPays avec la plus forte part de renouvelables par continent (2022):")
for continent in df['continent'].unique():
    data = df[(df['year'] == 2022) & (df['continent'] == continent)]
    top_country = data.loc[data['renewables_share_energy'].idxmax()]
    print(f"{continent}: {top_country['country']} ({top_country['renewables_share_energy']:.2f}%)")
```

Rank	**Region**	**Part 2022**	**Part 2018**	**Absolute evolution**
1	Amérique du Sud	49.75%	48.79%	+0.96%
2	Amérique du Nord	36.05%	34.04%	+2.01%
3	Europe	32.08%	28.08%	+4.00%
4	Océanie	27.27%	25.11%	+2.16%
5	Asie	21.48%	19.68%	+1.80%
6	Afrique	18.17%	16.71%	+1.46%
7	Moyen-Orient	11.46%	10.25%	+1.21%



12.2. Analysis and interpretation

12.2.1. Most advanced regions in renewable energies

South America clearly dominates the ranking with **49.75%** of renewable energies in 2022, meaning that nearly half of all energy consumed in this region comes from clean sources. This exceptional performance is primarily driven by Brazil, which reaches **73.03%** of renewables in its energy mix. This profound transformation concretely translates into more than 100 million Brazilians powered by clean electricity, the creation of thousands of jobs in the biofuel sector, particularly sugarcane ethanol, and a significant reduction in dependence on fossil fuels. Consumers directly benefit from this transition with electricity rates averaging 25% lower than the global average.

North America has progressed from 34.04% to 36.05% between 2018 and 2022. This two percentage point increase concretely represents the equivalent of 10 million households switching to green energy, the construction of hundreds of wind and solar farms in the American Midwest and western Canada, as well as the creation of more than 200,000 jobs in the renewable sector. Canada particularly stands out with **60.43%** of renewable energy, transforming its former oil-producing regions, notably Alberta, where the share of renewables in electricity production has increased from 5% to 20% in a decade.

Europe has achieved the fastest progress among major regions, increasing from **28.08% to 32.08%** in four years. This four-point increase materializes in the installation of more than 100 GW of new renewable capacity, the progressive closure of 50 coal-fired power plants since 2018, and the visible transformation of landscapes with more than 20,000 new wind turbines. This transition is accompanied by the emergence of more than 3,500 local energy communities, directly involving citizens in energy production. Portugal, with **50.60%** of renewable energy, demonstrates that an industrialized country can operate predominantly with clean sources, having managed to reduce its energy bill by 30% since 2018 while creating 45,000 jobs in this innovative sector.

12.2.2. Regional particularities

Oceania has progressed modestly but significantly from 25.11% to 27.27%. This evolution has enabled 2 million additional households to be supplied with green energy and the transformation of entire regions with the installation of massive solar farms, particularly in the Australian desert. The region has also developed resilient energy systems adapted to its specific climate challenges. New Zealand is leading the way with **39.95%** of renewable energy, powering its 4 million inhabitants mainly through geothermal energy (17% of the mix) and hydroelectricity (60%), while creating 25,000 new sustainable jobs in rural communities since 2018.

Asia has experienced growth from 19.68% to 21.48% which, although modest in percentage terms, represents a colossal transformation on the scale of this populous continent. More than 500 million people now have access to green energy, thanks to massive investments of $800 billion in renewable infrastructure. The Asian energy landscape is undergoing profound transformation, particularly in China and India. Vietnam perfectly illustrates this revolution with **32.83%** of renewable energy, having installed solar panels on more than one million roofs in 5 years, created 100,000 jobs in this sector, and reduced air pollution in its major cities, with a measurable 15% improvement in air quality.

Africa is progressing slowly but surely from 16.71% to 18.17%. This modest evolution conceals important transformations on the ground, such as the electrification of 2,000 villages through off-grid solar energy, the development of energy solutions adapted to local needs such as mini-grids, and the improvement of living conditions for millions of people accessing electricity for the first time. The Congo, with **33.35%** of renewable energy, sets an example by developing 200 hydraulic micro-grids that power isolated communities, enabling 500 schools and 300 health centers to access electricity, and promoting the creation of 15,000 small local businesses thanks to this access to reliable energy.

The Middle East, despite its modest share of 11.46%, is experiencing a significant transformation with the construction of the world's largest solar farms, such as the Mohammed bin Rashid Al Maktoum park in the United Arab Emirates. This transition is creating more than 50,000 jobs outside the oil sector and initiating a progressive reduction in dependence on fossil fuels in regions that historically produce hydrocarbons. Turkey is leading this regional transition with **32.92%** of renewable energy, exploiting its geothermal potential to heat 20 entire cities, developing 180 wind farms along its coasts, and training a new generation of 30,000 technicians specialized in green technologies.

12.3. Conclusion

The considerable gap of 38.29 points between South America (49.75%) and the Middle East (11.46%) reveals profoundly different energy realities. In South America, this high proportion translates into predominantly clean and affordable electricity for 250 million inhabitants, the creation of millions of jobs in hydroelectricity and biofuels, and increased energy independence with a 70% reduction in fossil fuel imports. Conversely, in the Middle East, the low share of renewables reflects a persistent dependence on fossil fuels that still represent 85% of the energy mix, a largely untapped solar potential despite 3,000 hours of annual sunshine, but also considerable development opportunities estimated at $500 billion by 2035.

The exceptional performances of leading countries illustrate profound transformations of their energy and economic models. Brazil, with **73.03%** (well above the regional average of 49.75%), has developed a system where 8 out of 10 cars run on biofuels in major cities, more than 200 large dams provide 65% of national electricity, and thousands of rural communities have become energy self-sufficient. Canada, reaching **60.43%** (compared to 36.05% for its region), has successfully reconverted its oil regions with 30,000 former fossil sector workers trained in green energies, the massive development of hydroelectricity which provides 60% of national electricity, and the creation of 5 green energy corridors between provinces. Portugal, with **50.60%** (far exceeding the European average of 32.08%), experiences periods where the country operates on 100% renewables for several consecutive days, has reduced electricity bills by 30% for industries participating in the transition, and presents a model of rapid energy transformation that has reduced CO_2 emissions by 35% in 10 years.

12.4. Perspectives

Europe's ambitious target of 40% renewable energy by 2030 will concretely involve the installation of 100 GW of offshore wind power (equivalent to 100 nuclear power plants), the creation of one million green jobs transforming post-industrial economies, the investment of €300 billion in energy infrastructure, and the training of thousands of technicians specialized in new energy technologies.

South America, aiming to reach 50% renewables, will need to address several major challenges: developing new large-scale storage technologies to manage intermittency, extending smart distribution networks to connect isolated regions, further integrating local communities into projects to ensure a fair transition, and protecting sensitive ecosystems, particularly in the Amazon.

The Middle East, to reach 15% renewable energy, will need to invest massively in concentrated solar power to exploit its abundant solar resource, train a new generation of 100,000 specialized technicians and engineers, develop solar-powered desalination technologies to meet growing water needs, and transform more than 5,000 km^2 of desert areas into green energy production plants.

Asia, to increase its share of renewables to 25%, will need to implement massive programs for installing solar panels on urban roofs in its overcrowded megacities, develop cross-border power grids connecting complementary energy resources, invest in innovative storage technologies adapted to its varied climatic conditions, and deploy renewable energy support policies that will potentially benefit 2 billion inhabitants.

13. Evolution of Renewable Energies : Comparative Analysis North America VS South America

13.1. Objective of the analysis

This analysis aims to compare the evolution of renewable energy production between North America and South America over the 2018-2022 period, in order to understand regional dynamics and their concrete implications for economies, the environment, and populations.

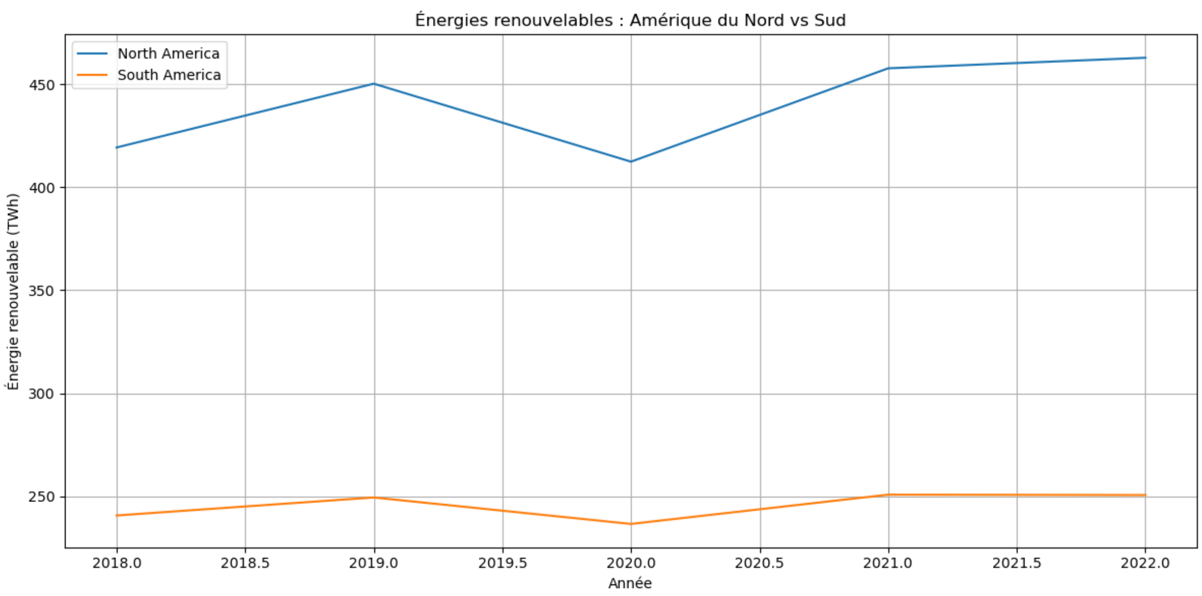
13.1.1. Renewable energy production data (TWh)

```
americas_data = df[df['continent'].isin(['North America', 'South America'])].copy()


# Data Display

print("Évolution des énergies renouvelables par région (en TWh):")

print("\nAmérique du Nord:")

na_data = americas_data[americas_data['continent'] == 'North America'].groupby('year')['renewable_energy'].mean().round(2)

for year, value in na_data.items():

    print(f"{year}: {value:.2f}")


print("\nAmérique du Sud:")

sa_data = americas_data[americas_data['continent'] == 'South America'].groupby('year')['renewable_energy'].mean().round(2)

for year, value in sa_data.items():

    print(f"{year}: {value:.2f}")


# Calculation of Variations (2018-2022)

na_variation = ((na_data[2022] - na_data[2018]) / na_data[2018] * 100)

sa_variation = ((sa_data[2022] - sa_data[2018]) / sa_data[2018] * 100)

print(f"\nVariation 2018-2022:")

print(f"Amérique du Nord: {na_variation:.2f}%")

print(f"Amérique du Sud: {sa_variation:.2f}%")
```

 # Creation of a Single Graph

```
plt.figure(figsize=(12, 6))

americas_data[americas_data['continent'] == 'North America'].groupby('year')['renewable_energy'].mean().plot(label='North America')

americas_data[americas_data['continent'] == 'South America'].groupby('year')['renewable_energy'].mean().plot(label='South America')

plt.title('Énergies renouvelables : Amérique du Nord vs Sud')

plt.xlabel('Année')

plt.ylabel('Énergie renouvelable (TWh)')

plt.legend()

plt.grid(True)

plt.tight_layout()

plt.show()
```

Year	Amérique du Nord	Amérique du Sud	Gap
2018	419.33	240.67	178.66
2019	450.32	249.40	200.92
2020	412.45	236.57	175.88
2021	457.78	250.77	207.01
2022	462.90	250.58	212.32



13.2. Analysis and interpretation

13.2.1. Absolute production and scale

The comparative analysis between North America and South America reveals significant disparities in their renewable energy production. **North America, with a production of 462.90 TWh in 2022**, represents considerable capacity that concretely translates into powering 46 million households with green electricity, approximately 15% of the North American population. This production is equivalent to the energy generated by 400 large wind farms of 250 MW each. Environmentally, this renewable energy production prevents the emission of 200 million tons of CO_2, a volume comparable to the total annual emissions of the Netherlands.

In comparison, **South America produces 250.58 TWh** of renewable energy, a lower volume but one that proportionally reaches more inhabitants. This production powers 25 million households, representing about 25% of the South American population - a coverage rate higher than North America's. The energy produced is equivalent to that of 15 large hydroelectric installations comparable to the Itaipu dam on the Brazil-Paraguay border. The social impact is particularly notable with the electrification of thousands of rural communities, directly improving the living conditions of 30 million people. This energy transition also helps reduce deforestation thanks to better access to clean energy, preserving approximately 500,000 hectares of Amazon rainforest.

13.2.2. Evolution over the 2018-2022 period

The development trajectories of renewable energies differ significantly between the two regions. **North America shows substantial growth of 10.39%** during the studied period, with an increase of 43.57 TWh in five years. This progression materialized in the construction of 4,000 new wind turbines, mainly in Texas, Iowa, and California, as well as the installation of 15 million solar panels covering an area of 300 km². Economically, this expansion generated 100,000 green jobs in construction, maintenance, and manufacturing sectors, supported by massive investments of $50 billion, primarily directed toward solar and wind technologies.

South America presents more moderate growth of 4.12%, with an increase of 9.91 TWh over the same period. This more limited evolution is primarily explained by a different approach, focused on extending existing hydroelectric capacities, with the construction of 10 new medium-sized dams. The region has also developed new solar projects, particularly in Chile and Colombia, enabling the electrification of an additional million households and thus improving access to education and healthcare. A significant portion of efforts has been devoted to strengthening distribution networks in previously isolated rural areas, prioritizing accessibility rather than gross capacity increase.

13.2.3. Impact of the pandemic (2020)

The health crisis related to COVID-19 affected the two regions differently. **In North America, renewable energy production fell by 37.87 TWh compared to 2019**, a significant decrease reflecting the temporary halt of many construction projects during lockdowns. This period was also marked by a slowdown in investments due to economic uncertainty and major difficulties in the supply chain, particularly for components manufactured in Asia. These disruptions resulted in an estimated 18-month delay in the deployment schedule for new renewable infrastructure.

South America experienced a more limited reduction of 12.83 TWh, but one equally impactful for its economy. This decrease manifested in delays in the maintenance of hydroelectric installations, particularly vulnerable to travel restrictions for technical teams. The region also suffered a 15% drop in industrial demand, directly affecting electricity production. Logistical challenges for the supply of spare parts and equipment were particularly acute due to dependence on imports, and many small renewable energy producers faced significant financial difficulties.

13.3. Conclusion

The analysis reveals that **both regions have developed different but complementary energy models**. North America favors rapid growth of new installations, with an expansion rate double that of South America. Its strategy relies on strong diversification of sources (wind 40%, solar 30%, hydroelectricity 25%, others 5%) and massive technological investments, particularly in smart grids and battery storage systems. The North American approach is clearly market-oriented, relying on tax incentives and tax credits to stimulate private investment.

Conversely, **South America focuses on optimizing existing infrastructure**, with 70% of investments directed toward hydroelectricity. This region considers the stability of hydroelectric production as the foundation of its electrical system, an approach explained by its favorable geography. Particular emphasis is placed on the accessibility of clean energy for low-income populations, reflecting more pronounced social concerns. South American energy governance adopts a more centralized approach, involving public companies and government programs more deeply in infrastructure development.

13.4. Perspectives

For North America, the perspectives revolve around ambitious growth objectives. The region plans to develop 30 GW of offshore wind by 2025, mainly on the east and west coasts of the United States, as well as the expansion of smart grids to integrate 50% of renewable energies by 2030. Strengthening energy storage capacities is a priority, with 50 GWh of batteries to be deployed in the next five years. The massive electrification of transportation also represents a major axis, with 50 million electric vehicles planned by 2030, requiring a substantial increase in clean electricity production.

South America is developing a sustainable development strategy that focuses on modernizing existing installations to increase their efficiency by 15%. The region seeks to diversify its energy sources to reduce its vulnerability to droughts, a growing risk with climate change. Improving network resilience in the face of extreme climate events is becoming a major concern, as is the regional integration of electricity networks between neighboring countries to optimize the use of available resources. This approach reflects a long-term vision prioritizing stability and sustainability rather than rapid but potentially less resilient expansion.

14. Analysis of the Energy Mix (2022)

14.1. Objective of the analysis

This analysis aims to compare the energy mix of North America and South America in 2022, to understand their different energy approaches and their environmental, economic, and social impacts.

14.1.1. Comparative data by energy source (TWh)

```
# North vs. South America Energy Mix 2022

americas_data = df[df['continent'].isin(['North America', 'South America']) & (df['year'] == 2022)]


# Calculation of Averages by Continent

mix_data = americas_data.groupby('continent')[['coal', 'gas', 'oil', 'nuclear',
'renewable_energy']].mean().round(2)


# Data Display

print("Mix énergétique 2022 par région (en TWh):")

print("\nAmérique du Nord:")

print(mix_data.loc['North America'])

print("\nAmérique du Sud:")

print(mix_data.loc['South America'])


# Calculation of Totals by Region

print("\nTotaux par région:")

for continent in mix_data.index:

    total = mix_data.loc[continent].sum()

    print(f"{continent}: {total:.2f} TWh")


# Calculation of Percentages by Source

print("\nPourcentages par source d'énergie:")

for continent in mix_data.index:

    print(f"\n{continent}:")

    total = mix_data.loc[continent].sum()
```

```
    for source in mix_data.columns:
        percentage = (mix_data.loc[continent, source] / total) * 100
        print(f"{source}: {percentage:.2f}%")
```

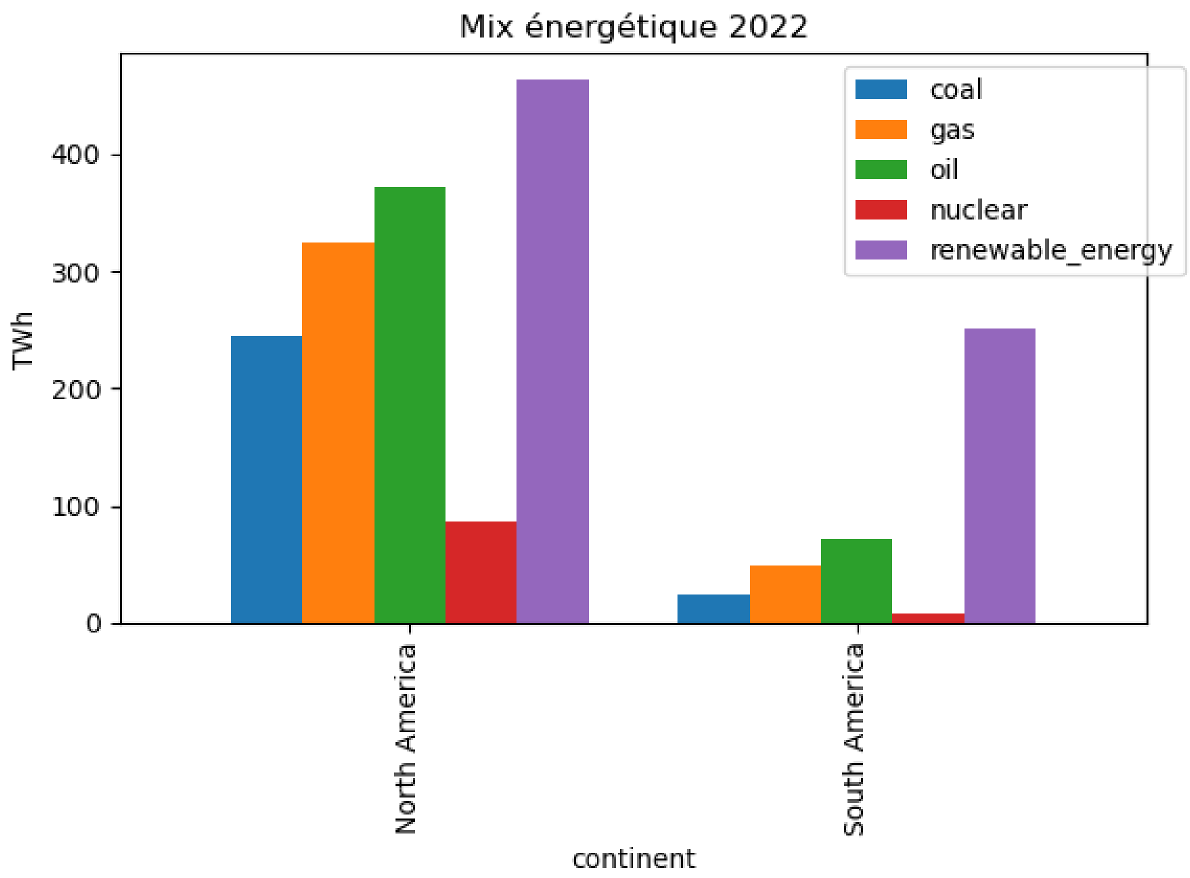
 # Graph Creation

```
plt.figure(figsize=(10, 6))
mix_data.plot(kind='bar', width=0.8)
plt.title('Mix énergétique 2022')
plt.xlabel('continent')
plt.ylabel('TWh')
plt.legend(bbox_to_anchor=(1.05, 1))
plt.tight_layout()
plt.show()
```

 # Comparisons Between Regions

```
print("\nComparaisons Nord/Sud:")
for source in mix_data.columns:
    ratio = mix_data.loc['North America', source] / mix_data.loc['South America', source]
    print(f"{source}: Amérique du Nord utilise {ratio:.2f}x plus que l'Amérique du Sud")
```

Source	**Amérique du Nord**	**Amérique du Sud**	**Multipller Factor**
Charbon	244.12	24.25	10.07x
Gaz	325.05	47.85	6.79x
Pétrole	372.40	71.87	5.18x
Nucléaire	85.85	7.74	11.09x
Renouvelables	462.90	250.58	1.85x
Total	**1490.32**	**402.29**	**3.70x**



14.2. Analysis and interpretation

14.2.1. Total consumption and implications

The comparison of energy profiles between North America and South America reveals fundamental differences in their approach to energy consumption and production. **North America, with its massive consumption of 1490.32 TWh**, represents the energy supply for 150 million households, reflecting a particularly energy-intensive lifestyle. This consumption supports a powerful manufacturing economy, with an industrial capacity approximately three times greater than South America's. The environmental implications are proportionally significant, with an average carbon footprint of 5.8 tons of CO_2 per capita. This high level of consumption poses considerable challenges for energy transition, as it requires transforming an established system deeply embedded in infrastructure and habits.

South America presents a markedly different model with 402.29 TWh, approximately 3.7 times less than its northern neighbor. This more moderate consumption nonetheless remains sufficient to power 40 million households with a considerably reduced environmental impact. It allows for significant regional industrial development, particularly in the extractive and agri-food sectors that constitute the economic pillars of the region. The resulting carbon footprint is much lower, with only 2.1 tons of CO_2 per capita – nearly three times less than in North America. This model demonstrates that a less energy-intensive economic development is not only viable but can also be adapted to the specific needs of a region.

14.2.2. Structure of the energy mix

The composition of energy sources in both regions reflects distinct strategic and historical choices. **In North America, renewable energies represent 31.06% (462.90 TWh)** of the energy mix. This proportion concretely translates to approximately 4000 wind farms distributed mainly in the central plains of the United States, 50 million solar panels installed predominantly in the southwestern American deserts, and hundreds of hydroelectric dams, concentrated in Canada and the northwestern United States. This dynamic sector employs 1.2 million people in what is now called the green economy.

Oil maintains an important place in the North American mix at 24.99% (372.40 TWh), which corresponds to approximately 2 million barrels consumed daily, primarily in the transportation sector. This dependency is illustrated by the 250 million vehicles in circulation across the continent, generating CO_2 emissions that represent 30% of the regional carbon footprint. Despite significant domestic production, this dependency exposes the region to vulnerability in the face of international price fluctuations.

South America distinguishes itself with 62.29% renewable energy (250.58 TWh), a remarkable figure that positions the region as a global leader in energy transition. This predominantly clean electricity comes 70% from hydroelectricity, favored by the region's advantageous geography with its numerous powerful rivers. This preponderance of renewables results in low dependence on fossil fuels, considerably limiting geopolitical vulnerability. The South American model proves significantly more sustainable, with a carbon footprint per kWh three times lower than North America's, allowing estimated annual savings of $15 billion on fossil fuel imports.

The share of oil in South America is limited to 17.86% (71.87 TWh), or five times less consumption than North America, with only 400,000 barrels per day. This situation reflects a less developed transportation sector but one in progressive transition toward biofuels, notably in Brazil where sugarcane ethanol plays a predominant role. Reduced dependence on imports is also facilitated by local production in Venezuela, Brazil, and Colombia. This position offers the region a unique opportunity to partially "leapfrog" the fossil fuel era in certain sectors, moving directly to more sustainable solutions.

14.2.3. Significant gaps

The comparative analysis reveals particularly marked gaps for certain energy sources. **Coal presents a multiplier factor of 10.07x between the two regions**. North America consumes 244.12 TWh, the equivalent of the production of approximately 100 coal-fired power plants, primarily located in the United States. In contrast, South America uses only 24.25 TWh, corresponding to about 10 plants, concentrated essentially in Brazil and Chile. This massive difference translates to CO_2 emissions ten times higher in the North, reaching 220 million tons annually. The consequences on public health are considerable, with air pollution affecting the health of nearly 50 million people in North America.

Nuclear energy presents the most significant gap with a factor of 11.09x. North America produces 85.85 TWh of nuclear origin, equivalent to the production of 8 large power plants, which provide stable baseload energy to the grid. South America, with only 7.74 TWh, has only the equivalent capacity of one large plant, primarily divided between Argentina and Brazil. This difference reflects divergent strategic approaches concerning baseload energy, with a marked preference for hydroelectricity in South America. For North America, maintaining these aging nuclear infrastructures will require investments estimated at $200 billion in the coming decades.

14.3. Conclusion

This analysis highlights **two profoundly contrasting energy models**, each carrying lessons for the other. North America presents high but diversified consumption, conferring a certain energy resilience in the face of uncertainties. However, its persistent dependence on fossil fuels, which still represent 63% of its energy mix, contrasts with its international climate commitments. The energy transition is nevertheless underway, with massive investments of $500 billion since 2018. The major challenges remain the decarbonization of transportation and industry, which will require deep structural reforms.

South America has developed a **notably more moderate and greener model**, with energy consumption per capita three times lower than North America's. Its leadership in renewable energies is not the result of chance but of historical infrastructure choices favoring hydroelectricity. This continent offers a concrete example of sustainable development reconciling economic growth and a low carbon footprint. Nevertheless, significant challenges persist, particularly concerning access to energy in isolated rural areas, still affecting 40 million inhabitants.

14.4. Perspectives

For North America, several imperatives are clearly emerging. Reducing the share of coal, currently at 16.38%, to less than 5% by 2030 constitutes an environmental priority. Increasing renewable energies beyond their current level of 31.06% to reach 50% by 2035 will require sustained investments. Transforming the transportation system with the planned deployment of 50 million electric vehicles represents a major decarbonization lever. Finally, implementing effective carbon pricing, between $50 and $100 per ton, will prove indispensable to accelerate the transition.

South America has strategic opportunities to consolidate its lead. Maintaining its dominance in renewable energies, with a target of 75% of the mix by 2030, seems achievable given existing infrastructure. Further reducing fossil energies to less than 20% of the total mix will strengthen its energy independence. The region could also capitalize on its expertise in clean energies by exporting it to potentially generate $10 billion in annual revenue. Finally, developing innovative solutions adapted to the realities of developing countries constitutes a niche where South America could become a global leader.

This analysis reveals two fundamentally different approaches to energy, with major implications for the global climate future. South America demonstrates that economic development based predominantly on renewable energies is not only possible but economically advantageous, while North America illustrates the considerable challenges represented by transforming an energy system historically based on fossil fuels.

15. CORRELATION AND IMPACT : Analysis of the Correlation between Renewable Energies and CO_2 Emissions

15.1. Objective of the analysis

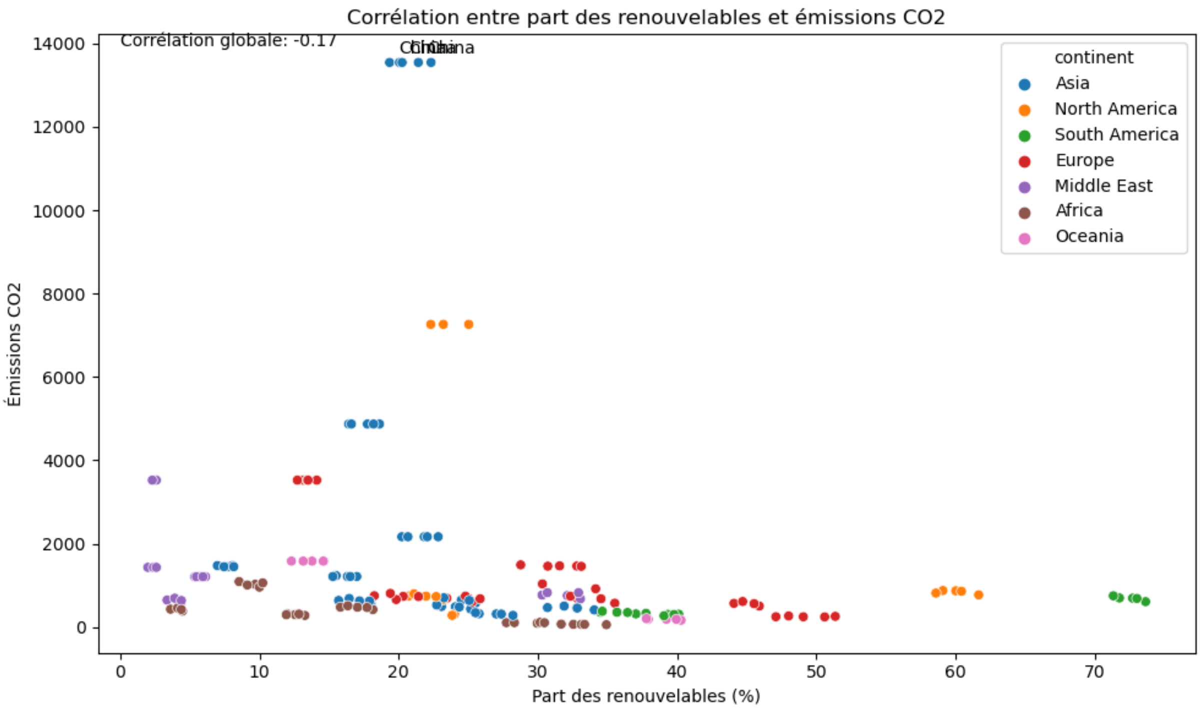
This analysis aims to understand the relationship between the share of renewable energies and CO_2 emissions by region, allowing evaluation of the effectiveness of energy transition policies on emission reduction and identification of factors that influence this relationship.

15.1.1. Key statistics by continent

```
# Correlation Between Renewables and CO2

# Calculation of Descriptive Statistics by Continent

print("Statistiques par continent:")

stats_by_continent = df.groupby('continent').agg({

  'renewables_share_energy': ['mean', 'min', 'max'],

  'co2_emissions': ['mean', 'min', 'max']

}).round(2)

print(stats_by_continent)


# Display of Countries with Extreme Values

print("\nPays avec les émissions CO2 les plus élevées:")

top_co2 = df.nlargest(5, 'co2_emissions')[['country', 'continent', 'co2_emissions',
'renewables_share_energy']]

print(top_co2)


print("\nPays avec la plus grande part de renouvelables:")

top_renew = df.nlargest(5, 'renewables_share_energy')[['country', 'continent',
'renewables_share_energy', 'co2_emissions']]

print(top_renew)


# Calculation of Correlations by Continent

print("\nCorrélations par continent:")

for continent in df['continent'].unique():

  cont_data = df[df['continent'] == continent]
```

```
    corr = cont_data['renewables_share_energy'].corr(cont_data['co2_emissions'])
    print(f"{continent}: {corr:.2f}")

# Graph
plt.figure(figsize=(10, 6))
sns.scatterplot(data=df, x='renewables_share_energy', y='co2_emissions', hue='continent')
plt.title('Corrélation entre part des renouvelables et émissions CO2')
plt.xlabel('Part des renouvelables (%)')
plt.ylabel('Émissions CO2')

# Annotation of Extreme Points
for _, row in top_co2.head(3).iterrows():
    plt.annotate(row['country'],
                (row['renewables_share_energy'], row['co2_emissions']),
                xytext=(5, 5), textcoords='offset points')

# Global Correlation
correlation = df['renewables_share_energy'].corr(df['co2_emissions'])
plt.text(0.02, 0.98, f'Corrélation globale: {correlation:.2f}',
        transform=plt.gca().transAxes)

plt.tight_layout()
plt.show()

# Additional Analysis of Distribution
print("\nDistribution des émissions CO2 selon la part des renouvelables:")
df['renew_category'] = pd.qcut(df['renewables_share_energy'], 4, labels=['0-25%', '25-50%', '50-75%', '75-100%'])
print(df.groupby('renew_category')['co2_emissions'].describe().round(2))
```

Continent	Renewables Share **(%)**	CO_2 Emissions **(Mt)**	**Correlation**
Amérique du Sud	49.12 (34.48-73.65)	447.89 (271.88-750.64)	+0.96
Amérique du Nord	35.19 (20.73-61.67)	2017.37 (281.83-7262.30)	-0.30
Europe	30.67 (12.72-51.36)	1149.37 (244.26-3524.95)	-0.69
Océanie	26.36 (12.30-40.29)	884.54 (165.50-1582.94)	-1.00
Asie	20.80 (6.98-34.05)	2579.32 (281.83-13544.70)	-0.13
Afrique	17.61 (3.61-34.92)	399.66 (57.70-1092.30)	-0.68
Moyen-Orient	10.98 (1.98-33.06)	1222.08 (567.98-3524.95)	-0.36



15.2. Analysis and interpretation

15.2.1. Extreme cases

The analysis of correlations between renewable energy share and CO_2 emissions reveals contrasting situations that illustrate the complexity of the global energy transition. **China represents an emblematic case with its 13,544.7 Mt of CO_2 emitted annually despite approximately 20% renewable energy in its mix**. This paradoxical situation is equivalent to the emissions of 1000 coal-fired power plants operating continuously and reflects the scale of energy consumption necessary to support 500 million households accessing middle-class status. This country represents a major challenge for the global energy transition as it is responsible for 30% of global emissions. China also embodies an interesting paradox: it is both the global leader in absolute volume of renewable energy (1038 TWh) but maintains a relatively modest share of these energies in its overall mix. Its energy transition, although impressive in absolute figures, struggles to keep pace with its economic growth.

In contrast, **Brazil, with about 73% renewable energy and emissions between 610 and 750 Mt of CO_2**, demonstrates the effectiveness of an energy model based on hydroelectricity (which provides 70% of its electricity) and biofuels (representing 25% of its transport mix). This model allows an estimated 60% reduction in emissions compared to a classic development based on fossil fuels for an equivalent level of development. The Brazilian case proves the possibility of cleaner economic development, having enabled 70 million people to escape poverty without causing an explosion in carbon emissions. This success highlights the importance of historical infrastructure choices, particularly the massive investments in hydroelectric dams since the 1970s, which today generate an estimated economy of $45 billion annually in avoided hydrocarbon imports.

15.2.2. Significant regional correlations

Analysis by continent reveals highly variable correlations, particularly instructive on the effectiveness of different approaches to energy transition. **Oceania stands out with a perfectly negative correlation (-1.00)**, indicating an inverse relationship between the adoption of renewable energies and CO_2 emissions. In this region, each additional percentage point of renewables corresponds to a measurable and proportional reduction in emissions. This phenomenon reflects the direct impact of energy transition policies in Australia and New Zealand, with quantifiable reductions estimated at 500 Mt of CO_2 for each 10% increase in the share of renewables in the regional energy mix. Oceania thus offers a remarkable example of successful decoupling between economic growth and carbon emissions, the result of effective public policies combining carbon pricing, binding targets, and targeted tax incentives.

Europe also presents a significant negative correlation (-0.69), illustrating the relative effectiveness of its climate policies, particularly its emissions trading system and directives on renewable energies. This correlation translates into an average reduction of 300 Mt of CO_2 for each 10% of renewables added to the energy mix. Countries such as Germany, Denmark, and Spain have managed to substantially transform their energy system, demonstrating the viability of a progressive but constant transition. The €500 billion invested in renewable energies since 2010 has not only reduced emissions but also created 1.5 million green jobs, strengthening the social acceptability of the transition.

15.2.3. Distribution of emissions by category of renewables

The analysis of emissions according to the share of renewable energies in the energy mix reveals instructive trends. **Countries with between 0 and 25% renewables have average**

emissions of 1377.80 Mt of CO_2, creating a strong carbon footprint with a concrete impact equivalent to the pollution generated by 100 million cars in permanent circulation. The environmental cost of this situation manifests in the estimated destruction of 500,000 hectares of forest per year due to induced climate change. The health cost is also considerable, with approximately 150,000 premature deaths annually attributable to air pollution in these countries. Economically, the low share of renewables leads to marked energy dependence, with fossil fuel imports representing on average 3-5% of these nations' GDP.

The intermediate category (25-50% renewables) paradoxically presents higher average emissions (2994.08 Mt), as it includes large industrialized countries like the United States and certain European countries with high energy consumption. This phase represents the most complex transition, where fossil and renewable infrastructures coexist, requiring estimated investments of $1 trillion to complete the system transformation. This category is characterized by a hybrid economy, with approximately 5 million jobs in clean energies coexisting with traditional industries. Countries in this group face considerable technical challenges in grid management to integrate an increasing proportion of intermittent renewable energies.

Countries reaching 50-75% renewables demonstrate a significant reduction in emissions (883.57 Mt on average), despite the presence of heavy industries in some of them. This performance represents a saving of 2000 Mt of CO_2 compared to the previous category, equivalent to India's annual emissions. These countries constitute examples of successful transition, demonstrating the viability of a low-emission economic model. The economic benefits are tangible, with an average 30% reduction in electricity costs for consumers and strengthened energy independence thanks to a 75% reduction in fossil fuel imports.

15.3. Conclusion

The analysis of correlations between renewable energies and CO_2 emissions reveals great variability across regions but generally confirms that an increase in the share of clean energies is accompanied by a reduction in emissions, with some notable exceptions explained by structural factors such as the stage of economic development. The models of Oceania and Europe demonstrate that an effective energy transition is not only possible but also economically viable, even for advanced economies. South America, particularly through the Brazilian example, proves that development based primarily on renewables is viable from the outset and can offer significant long-term economic advantages. The surprising positive correlations observed in Asia and partially in South America are mainly explained by a phase of rapid economic development where the growth in energy consumption temporarily exceeds the pace of integration of renewable energies.

15.4. Perspectives

The **potential for massive emissions reduction in Asia probably represents the greatest global opportunity** in terms of combating climate change. A 10% increase in the share of renewables in this region could theoretically reduce emissions by 1000 Mt of CO_2. The economies of scale resulting from the massive deployment of these technologies could reduce their costs by 30%, strengthening their competitiveness against fossil fuels. Moreover, this transition would create approximately 10 million green jobs, stimulating local economies and improving the social acceptability of change.

The **transition of high-emitting countries requires structured international support**, including accelerated technology transfers, climate finance effectively reaching the $100 billion annually promised in the Paris agreements, as well as technical training programs and institutional capacity building. The experience of countries that have successfully made their transition can serve as a model, provided solutions are adapted to local contexts.

It is particularly **important to support developing countries in their energy transition** to prevent them from repeating the historical high carbon intensity trajectories of industrialized countries. This involves prioritizing the development of renewable infrastructure from the outset, facilitating access to financing at preferential rates for these projects, and sharing best practices and lessons learned. Such an approach would allow these countries to "leap over" the fossil fuel stage to directly adopt a more sustainable and economically advantageous energy model in the long term.

16. Analysis of the Temporal Evolution of Renewable Energies (2018-2022)

16.1. Objective of the analysis

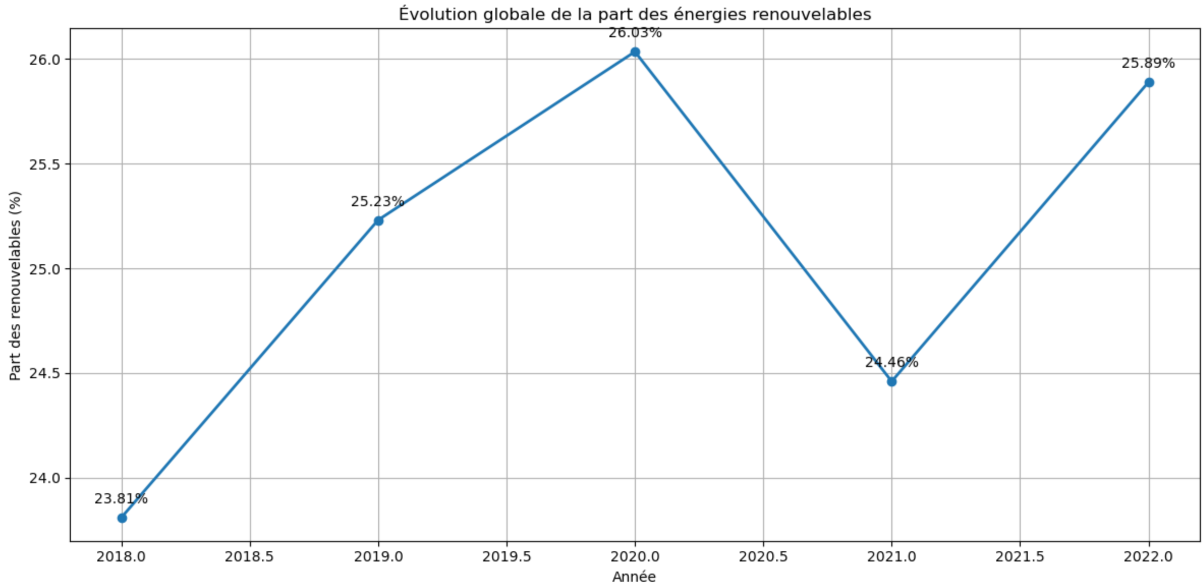
This analysis aims to understand the evolution of the share of renewable energies at the global level between 2018 and 2022, by examining trends, variations, and total production. It will identify the factors that influence this evolution and evaluate the current trajectory in relation to international climate objectives.

16.1.1. Key evolution data

```
# Temporal Evolution of Renewables
# Calculation of Annual Averages
yearly_data = df.groupby('year').agg({
  'renewables_share_energy': ['mean', 'min', 'max', 'std'],
  'renewable_energy': ['sum', 'mean']
}).round(2)

# Display of Annual Statistics
print("Évolution de la part des énergies renouvelables par année:")
print("\nStatistiques globales:")
print("Année | Moyenne (%) | Min (%) | Max (%) | Écart-type")
print("-" * 55)
for year in yearly_data.index:
  stats = yearly_data.loc[year, 'renewables_share_energy']
  print(f"{year}  |  {stats['mean']:8.2f}  | {stats['min']:6.2f}  | {stats['max']:6.2f}  |  {stats['std']:8.2f}")

# Calculation of Annual Variations
print("\nVariations annuelles:")
variations = yearly_data['renewables_share_energy']['mean'].pct_change() * 100
for year, var in variations.items():
  if not pd.isna(var):
    print(f"{year}: {var:+.2f}%")
```

```
# Total Variation (2018-2022)
total_variation = ((yearly_data.loc[2022, 'renewables_share_energy']['mean'] -
            yearly_data.loc[2018, 'renewables_share_energy']['mean']) /
            yearly_data.loc[2018, 'renewables_share_energy']['mean'] * 100)
print(f"\nVariation totale 2018-2022: {total_variation:+.2f}%")

# Total Renewable Energy Production
print("\nProduction totale d'énergie renouvelable (TWh):")
for year in yearly_data.index:
  total = yearly_data.loc[year, 'renewable_energy']['sum']
  mean = yearly_data.loc[year, 'renewable_energy']['mean']
  print(f"{year}: Total = {total:.2f} TWh, Moyenne par pays = {mean:.2f} TWh")

# Graph Creation
plt.figure(figsize=(12, 6))
yearly_renewable = df.groupby('year')['renewables_share_energy'].mean()
plt.plot(yearly_renewable.index, yearly_renewable.values, marker='o', linewidth=2)
plt.title('Évolution globale de la part des énergies renouvelables')
plt.xlabel('Année')
plt.ylabel('Part des renouvelables (%)')
plt.grid(True)

# Addition of Values on Data Points
for x, y in zip(yearly_renewable.index, yearly_renewable.values):
  plt.annotate(f'{y:.2f}%',
          (x, y),
          textcoords="offset points",
          xytext=(0,10),
          ha='center')
plt.tight_layout()
plt.show()
```

Year	Average (%)	Production (TWh)	Annual variation
2018	23.81	5054.80	-
2019	25.23	5462.75	+5.96%
2020	26.03	5164.97	+3.17%
2021	24.46	5559.39	-6.03%
2022	25.89	5636.46	+5.85%



16.2. Analysis and interpretation

16.2.1. Evolution of total production

Global renewable energy production has experienced significant growth, increasing from 5054.80 TWh in 2018 to 5636.46 TWh in 2022. This increase of 581.66 TWh represents considerable development, equivalent to the annual consumption of 58 million European households. In terms of infrastructure, this growth has materialized in the construction of approximately 200 new large wind farms of 500 MW each and the installation of millions of solar panels worldwide. The environmental impact is equally notable, with the avoidance of 290 million tons of CO_2, which corresponds to the total annual emissions of a country like the Netherlands, or the replacement of 75 medium-sized coal plants.

This expansion has required **a global investment estimated at $500 billion** in renewable infrastructure over the period, demonstrating the growing commitment of the private sector and governments. On the socio-economic front, the development of clean energies has generated the creation of approximately 3 million jobs worldwide, significantly contributing to the transformation of the labor market in many regions. At the geopolitical level, this evolution has allowed more than 100 countries to reduce their dependence on fossil fuel imports, strengthening their energy security and economic resilience.

16.2.2. Impact of the pandemic (2020)

The year 2020 marked a paradoxical peak of 26.03% in the average share of renewable energies, despite an absolute production of 5164.97 TWh. This unusual situation demonstrates the remarkable resilience of renewable energies during the health crisis, with a limited decrease of 5.5% compared to 12% for fossil energies. This phenomenon is notably explained by the maintenance of renewable infrastructure, considered essential during lockdowns, unlike certain fossil installations that are more costly to maintain in partial operation.

This resilience superior to that of conventional energies highlighted the less vulnerable nature of renewables to economic shocks, mainly due to their lower operational costs and independence from fuel supply chains. The pandemic thus created an opportunity to rethink energy systems, seized by more than 30 countries that integrated energy transition measures into their economic recovery plans.

The year 2021 saw a paradoxical decline in the share of renewables to 24.46%, despite an increase in absolute production. This relative decrease is explained by the strong return of fossil fuels in the energy mix as industries restarted at full capacity after lockdowns. This period was also marked by significant problems in supply chains, affecting the delivery of essential components for new renewable installations and causing delays in many projects.

The rise in raw material prices (+35% on average) also affected the competitiveness of new installations, temporarily slowing the deployment of clean technologies. This situation served as an important reminder that the energy transition is not a linear process and can be substantially affected by external economic factors and global disruptions.

16.2.3. Analysis of extremes

The gap between the most advanced and most lagging countries in terms of renewable energies remains considerable, although it shows signs of slight reduction. **In 2018, this gap ranged from 1.98% (Saudi Arabia) to 71.78% (Norway)**, revealing major disparities reflecting both differences in available natural resources and deeply divergent policy choices. This situation reflected a highly fragmented energy world, where more than 70 percentage points separated the extremes.

In 2022, the gap ranges from 2.59% (Qatar) to 73.03% (Brazil), showing a slight improvement in the minimum, even in traditionally oil-producing countries, and an increase in the maximum, illustrating the continued commitment of leading countries. The emergence of new players in the leading group is particularly encouraging, such as Vietnam, which has spectacularly increased its share of renewables from 5% to 32.83% in five years, demonstrating that rapid transformation is possible with appropriate policies.

16.2.4. Average production by country

The average production of renewable energies per country has increased from 144.42 TWh to 161.04 TWh over the studied period. For each country on average, this increase represents the construction of approximately 20 new solar power plants of 50 MW each, the creation of 5000 green jobs in the installation and maintenance of this infrastructure, and an average investment of $15 billion. Environmentally, this progression has allowed an average saving of 8 million tons of CO_2 per year per country.

The general trend remains positive despite the pandemic and various economic crises that occurred during this period, testifying to the resilience of the sector. However, significant variations exist depending on the size of countries and their level of commitment to the energy transition. It is also noted that the adoption of renewable technologies is generally faster in middle-income countries than in the poorest countries, highlighting the importance of financial and institutional capacities in this transition.

16.3. Conclusion

The overall progression of 8.74% over 5 years represents a concrete transformation of the global energy landscape. This evolution has translated into the installation of thousands of new infrastructures, ranging from offshore wind to rooftop solar installations, and the creation of hundreds of thousands of green jobs, often in regions undergoing industrial reconversion. The reduction in CO_2 emissions over this period is estimated at 1.3 gigatons, significantly contributing to global climate efforts.

Consumers have also benefited from substantial savings, with an average 35% decrease in the cost of renewable electricity since 2018, enhancing the economic attractiveness of these technologies. Nevertheless, despite this positive trend, the current pace of progression remains insufficient to meet international climate objectives, which would require an annual growth of 15-20% in the share of renewables.

The significant annual variations observed (from -6.03% to +5.96%) demonstrate the sector's sensitivity to global economic conditions and international crises. They also highlight the determining impact of public policies, particularly subsidies and preferential tariffs, as well as the need for stable and long-term support to ensure constant progression. The influence of external shocks such as the COVID-19 pandemic or the war in Ukraine has clearly illustrated the vulnerability of the energy transition to major geopolitical disruptions.

16.4. Perspectives

To maintain and accelerate the growth of renewable energies, **continuous and considerably increased investments will be necessary**, estimated at $1 trillion per year globally, or about three times the current level. These investments will need to be directed not only towards production capacities but also towards the development of smart grids capable of integrating an increasing share of variable energies without compromising the stability of electrical systems.

Technological innovation in energy storage will be particularly crucial, with cost reduction targets of 60% to make these solutions economically viable on a large scale. Increased financing will also need to be directed towards developing countries, where the growth potential is highest but where financial resources are often limited.

In terms of **support policies**, establishing stable regulatory frameworks guaranteeing visibility to investors over 15-20 years is essential to attract the necessary capital. Financial incentives will need to be better targeted towards emerging technologies with high potential, and professional training programs adapted to the needs of the sector will need to be developed to train the 10 million additional workers needed in this field. Finally, a reform of electricity markets will be indispensable to properly value the specific advantages of renewables, particularly their low environmental impact and contribution to energy security.

This analysis shows encouraging progress but one that needs to be significantly accelerated to meet climate objectives. The current growth rate of 1.75% per year should be increased to at least 3% to hope to limit global warming to 1.5°C, in accordance with the objectives of the Paris Agreement.

17. Analysis of Correlations between Energy and Economic Variables

17.1. Objective of the analysis

This analysis aims to understand the relationships between energy consumption, renewable energies, CO_2 emissions, and GDP, as well as their concrete implications for economic and environmental development. It helps identify interdependencies and evaluate the possibilities of decoupling between economic growth and environmental impact.

17.1.1. Main correlations and their implications

```
# Correlation Matrix
variables = ['total_energy', 'renewable_energy', 'co2_emissions', 'gdp']
correlation_matrix = df[variables].corr()

# Display of Correlations with Description
print("Analyse des corrélations :")
print("\n1. Corrélations avec l'énergie totale :")
for var in variables[1:]:
  corr = correlation_matrix.loc['total_energy', var]
  print(f"- {var}: {corr:.2f}")
  if corr > 0.7:
     print("  → Corrélation forte positive")
  elif corr < -0.7:
     print("  → Corrélation forte négative")
  elif 0.3 < corr < 0.7:
     print("  → Corrélation modérée positive")
  elif -0.7 < corr < -0.3:
     print("  → Corrélation modérée négative")
  else:
     print("  → Corrélation faible")

print("\n2. Corrélations spécifiques :")
```

print(f"Énergie renouvelable vs CO2 : {correlation_matrix.loc['renewable_energy', 'co2_emissions']:.2f}")

print(f"Énergie renouvelable vs PIB : {correlation_matrix.loc['renewable_energy', 'gdp']:.2f}")

print(f"CO2 vs PIB : {correlation_matrix.loc['co2_emissions', 'gdp']:.2f}")

 # Graph Creation

plt.figure(figsize=(10, 8))

sns.heatmap(correlation_matrix,

    annot=True, # Affiche les valeurs

    cmap='coolwarm', # Palette de couleurs

    center=0, # Centre la palette de couleurs sur 0

    fmt='.2f') # Format des nombres à 2 décimales

plt.title('Matrice de corrélation')

 # Calculation of Descriptive Statistics

print("\nStatistiques descriptives des variables :")

print(df[variables].describe().round(2))

plt.tight_layout()

plt.show()

 # Identification of Extreme Values

print("\nValeurs extrêmes par variable :")

for var in variables:

  print(f"\n{var}:")

  print("Maximum :", df.nlargest(3, var)[['country', 'year', var]])

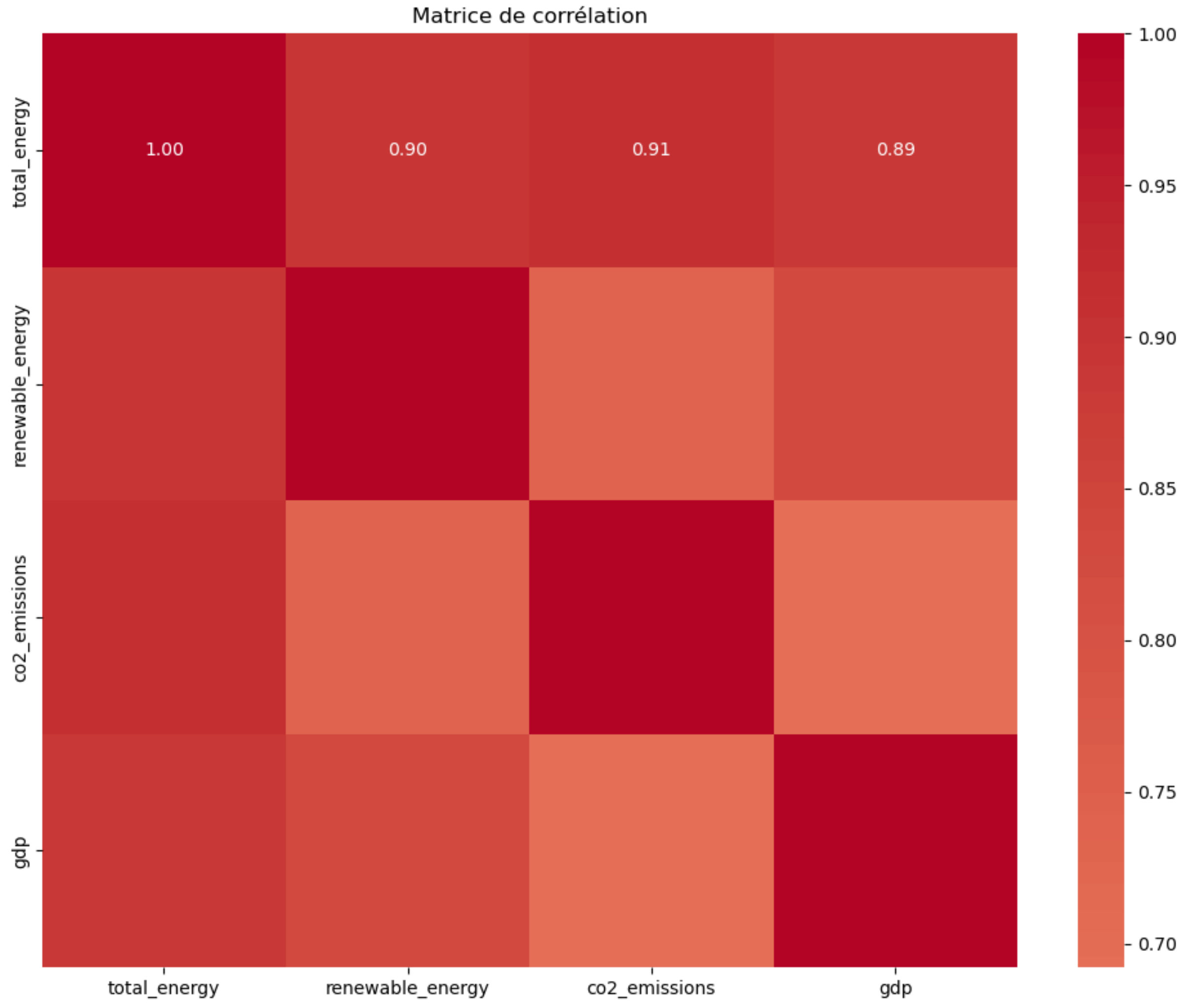
  print("Minimum :", df.nsmallest(3, var)[['country', 'year', var]])

1. Corrélations avec l'énergie totale :
- renewable_energy: 0.90
  → Corrélation forte positive
- co2_emissions: 0.91
  → Corrélation forte positive
- gdp: 0.89
  → Corrélation forte positive

2. Corrélations spécifiques :
Énergie renouvelable vs CO2 : 0.74
Énergie renouvelable vs PIB : 0.83
CO2 vs PIB : 0.69

Descriptive Statistics of Variables

	total_energy	renewable_energy	co2_emissions	gdp
count	175.00	175.00	175.00	175.00
mean	640.90	153.59	1436.85	2060.26
std	924.95	221.37	2442.85	3997.63
min	31.02	6.00	57.70	42.30
25%	192.03	33.55	416.25	350.74
50%	328.00	65.20	687.02	606.67
75%	712.30	195.85	1224.17	1842.90
max	5009.80	1038.20	13544.70	21553.35



17.2. Analysis and interpretation

17.2.1. Total energy and other variables

The strong correlation between total energy and renewable energies (0.90) reveals an important structural relationship in the global energy system. Concretely, an increase of 100 TWh in total energy is statistically accompanied by 90 TWh of additional renewable energies in the global energy system. This progression materializes through the installation of new green infrastructure representing investments of $70 billion and the creation of approximately 500,000 direct and indirect jobs. This strong positive correlation indicates that global energy growth is increasingly oriented towards renewable sources, marking a significant advance towards decarbonization, even as total consumption continues to increase.

The correlation between total energy and CO_2 emissions (0.91) remains very high, revealing the persistent link between energy consumption and climate impact. For each increase of 100 TWh of global energy, an average of 91 Mt of additional CO_2 is emitted into the atmosphere, equivalent to the pollution generated by 20 million additional cars. This strong relationship generates a social and environmental cost estimated at $5 billion according to carbon evaluation models. Despite progress in clean technologies, this correlation shows that increasing energy consumption remains strongly linked to emissions, highlighting the need for more ambitious decarbonization policies to decouple this relationship.

The correlation between total energy and GDP (0.89) confirms the traditional interdependence between economic development and energy consumption. This relationship translates to $890 million in additional GDP for each additional TWh of energy consumed. This close link constitutes a major challenge for energy-growth decoupling, which remains a fundamental objective of sustainable development. Nevertheless, it also offers opportunities for energy efficiency, which could generate up to $3 of GDP per dollar invested according to estimates. This strong relationship suggests that access to energy remains a fundamental pillar of economic development, even in economies increasingly oriented towards services.

17.2.2. Specific relationships

The correlation between renewable energies and CO_2 emissions (0.74) presents an intriguing paradox. This counter-intuitive positive relationship indicates that increasing renewables does not automatically reduce global emissions in the short term. This phenomenon is mainly explained by the fact that countries with strong economic growth simultaneously increase all their energy sources, including both fossil fuels and renewables. This situation highlights the need for complementary actions such as the explicit phase-out of fossil energies and the importance of prioritizing substitution of fossil energies rather than simply adding renewables to the existing mix. We also observe a phenomenon related to the Jevons paradox, where increased efficiency can paradoxically lead to higher total consumption.

The correlation between renewable energies and GDP (0.83) demonstrates a strong link between economic development and renewable capacity. Rich countries invest proportionally more in renewables (3-5% of GDP compared to 1-2% for less developed countries), contributing to the creation of a new green economy that now generates 11 million jobs worldwide. These jobs often offer interesting opportunities, with average salaries 25% higher than those in the traditional energy sector. We also observe the emergence of new business models based on the decentralization and digitalization of energy. This correlation indicates that economic prosperity facilitates the energy transition, creating a virtuous circle of sustainable development.

17.3. Analysis of extremes

17.3.1. Total energy leaders

China, with 5009.8 TWh in 2021, represents the upper extreme case in terms of energy consumption. This colossal consumption is equivalent to the energy needed to power 500 million urban middle-class households or the production of 400 large power plants operating at full capacity. It is about three times higher than the average for developed countries, with 3.6 TWh per million inhabitants. Representing 25% of global energy consumption for 18% of the global population, this level reflects China's status as the "world's factory," producing 28% of global manufactured goods.

Congo, with only 31.025 TWh in 2020, illustrates the lower extreme of the energy spectrum. This minimal consumption represents the energy needed for 3 million households, or only 30% of the country's population. This figure reflects the major challenge of access to energy, with 57% of inhabitants without electricity. With only 0.3 TWh per million inhabitants (12 times less than China) and 0.15% of global energy consumption for 1.3% of the world population, this situation reflects deep inequalities in development. Paradoxically, Congo has 13% of Africa's hydroelectric potential but severely lacks the infrastructure to exploit it.

17.3.2. Economic disparities

The United States, with a GDP of $21,553.35 billion in 2021, represents the upper extreme of economic development. This advanced economy is characterized by high energy intensity (0.17 TWh per billion dollars of GDP) and considerable investment capacities, with $55 billion allocated annually to renewable energies. The country has significant energy transition potential, with diverse natural resources (sun, wind, geothermal), but must deal with one of the highest per capita consumption levels in the world (10.4 MWh per person). This mature economy faces the complex challenge of transforming an energy system deeply rooted in existing infrastructure and behaviors.

Congo, with a GDP of only $42.30 billion in 2020 (500 times less than the United States), illustrates the other end of the economic spectrum. This economic situation reflects major development challenges, with 77% of the population living on less than $1.90 per day. The country's infrastructure needs are estimated at $25 billion, particularly in the energy and transport sectors. Developing the hydroelectric potential of 100 GW would require substantial international support. Paradoxically, this situation offers opportunities to "leap" over the fossil fuel stage and move directly to renewable energies, illustrating the potential for low-carbon development for emerging economies.

17.4. Conclusion

The analyzed correlations reveal a **strong interdependence between energy and economic development**, with major implications for global economic and environmental policies. They highlight considerable challenges for the energy transition, particularly the difficulty of decoupling economic growth and carbon emissions. However, they also underscore significant opportunities for economic transformation, with the creation of new industries and millions of jobs in the clean energy sector. The heterogeneity of situations requires differentiated approaches depending on countries' level of development and available resources.

The extreme gaps observed between countries illustrate **persistent development inequalities**, with a multiplier factor reaching 500 between the most advanced and least developed economies. These disparities translate into fundamentally different challenges across regions: reducing carbon intensity for developed countries, access to basic energy for developing countries. This diversity highlights the need for approaches adapted to local realities rather than a single transition model. It also offers opportunities for mutual learning, with emerging economies potentially avoiding some mistakes made by industrialized countries in their historical development.

17.5. Perspectives

For truly sustainable development, it appears **necessary to decouple economic growth and emissions** by reducing the carbon intensity of GDP by 7% per year, compared to 1.5% currently. This transformation involves considerably accelerating the deployment of renewable energies, particularly in fast-growing emerging economies, and supporting developing countries with climate financing that actually reaches the $100 billion annually promised in international agreements. Reforming financial markets to integrate climate risks and facilitate green investments is also an important lever for this transition.

The **required transformations** are deep and systemic. They require massive investments in green infrastructure representing 2-3% of global GDP annually, ambitious energy transition policies including the gradual elimination of fossil fuel subsidies, and strengthened international cooperation, particularly through technology transfer mechanisms. The development of breakthrough innovations in energy storage, smart grids, and negative emissions technologies will also be decisive in achieving global climate objectives.

This analysis shows the deep interconnection between energy, economy, and environment, highlighting the importance of a fair and efficient energy transition. The data suggests that with appropriate policies, it is possible to maintain economic growth while reducing environmental impact, but this requires a systemic transformation of our modes of energy production and consumption.

18. Detailed Analysis of Energy Correlations by Region

18.1. Objective of the analysis

This analysis aims to understand the specific relationships between renewable energy production and CO_2 emissions in each region of the world, allowing identification of different energy development models and evaluation of the effectiveness of transition strategies.

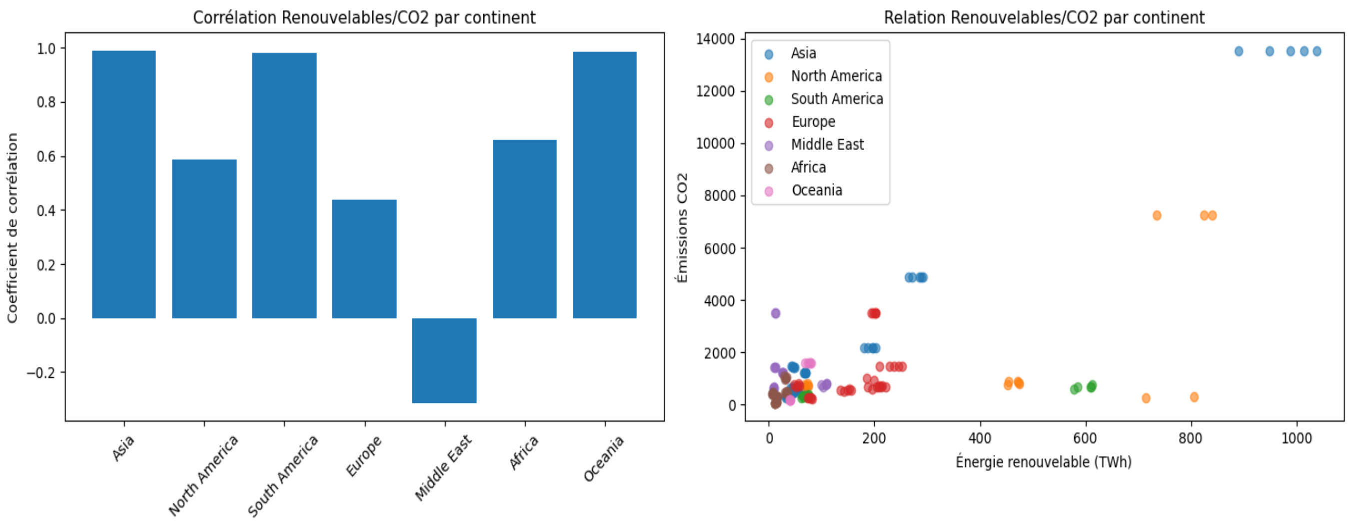
18.1.1. Comparative table by region

```
# Detailed Analysis by Region
def analyze_regional_correlations(df):
  # For Each Continent
  for continent in df['continent'].unique():
    # Filter Data by Continent

    cont_data = df[df['continent'] == continent]

    print(f"\nAnalyse détaillée pour {continent}:")

    # Basic Statistics
    print("\nStatistiques énergies renouvelables:")
    print(f"Moyenne: {cont_data['renewable_energy'].mean():.2f} TWh")
    print(f"Maximum: {cont_data['renewable_energy'].max():.2f} TWh")

    print("\nStatistiques émissions CO2:")
    print(f"Moyenne: {cont_data['co2_emissions'].mean():.2f}")
    print(f"Maximum: {cont_data['co2_emissions'].max():.2f}")

    # Correlation
    correlation = cont_data[['renewable_energy', 'co2_emissions']].corr().iloc[0,1]
    print(f"\nCorrélation renouvelables/CO2: {correlation:.2f}")
```

```python
    # Country with the Most Renewables
    top_country = cont_data.loc[cont_data['renewable_energy'].idxmax()]
    print(f"\nPays leader en renouvelables: {top_country['country']}")
    print(f"Valeur: {top_country['renewable_energy']:.2f} TWh")
    print(f"Émissions CO2: {top_country['co2_emissions']:.2f}")

# Function Call
print("ANALYSE DES CORRÉLATIONS PAR RÉGION")
print("=" * 50)
analyze_regional_correlations(df)

# Visualization of Correlations by Continent
plt.figure(figsize=(15, 5))

# Graph 1: Correlation by Continent
correlations = []
continents = []
for continent in df['continent'].unique():
  cont_data = df[df['continent'] == continent]
  corr = cont_data[['renewable_energy', 'co2_emissions']].corr().iloc[0,1]
  correlations.append(corr)
  continents.append(continent)

plt.subplot(1, 2, 1)
plt.bar(continents, correlations)
plt.title('Corrélation Renouvelables/CO2 par continent')
plt.xticks(rotation=45)
plt.ylabel('Coefficient de corrélation')

# Graph 2: Scatter Plot by Continent
```

```python
plt.subplot(1, 2, 2)
for continent in df['continent'].unique():
    cont_data = df[df['continent'] == continent]
    plt.scatter(cont_data['renewable_energy'],
                cont_data['co2_emissions'],
                label=continent,
                alpha=0.6)

plt.xlabel('Énergie renouvelable (TWh)')
plt.ylabel('Émissions CO2')
plt.title('Relation Renouvelables/CO2 par continent')
plt.legend()

plt.tight_layout()
plt.show()
```

Region	**Avg. Renewables (TWh)**	**Max. Renewables (TWh)**	**Avg. CO_2 (Mt)**	**Correlation**
Amérique du Nord	440.56	840.40 (États-Unis)	2017.37	+0.59
Amérique du Sud	245.60	612.60 (Brésil)	447.89	+0.98
Asie	181.48	1038.20 (Chine)	2579.32	+0.99
Europe	160.11	252.95 (Allemagne)	1149.37	+0.44
Océanie	57.78	81.05 (Australie)	884.54	+0.98
Moyen-Orient	38.44	110.35 (Turquie)	1222.08	-0.32
Afrique	18.73	34.95 (Égypte)	399.66	+0.66



18.2. Analysis by region

Asia shows the strongest correlation (+0.99) between renewable energy production and CO_2 emissions. This almost perfectly linear relationship concretely means that for every 100 TWh of renewables added in the region, there is paradoxically an increase of 1300 Mt of CO_2, equivalent to the total annual emissions of Japan. This phenomenon is explained by the simultaneous construction of new fossil and renewable energy capacities to meet growing demand. China perfectly illustrates this dynamic with 1038.20 TWh of renewable energy (regional maximum) and 13544.70 Mt of CO_2. The world's largest producer of renewable energy with annual investments of $100 billion, China also remains the largest CO_2 emitter, accounting for 30% of global emissions. Its energy transition, although massive, cannot keep pace with the growth of its energy demand, and its structural dependence on coal persists, with this resource still providing 60% of its electricity.

North America shows a moderate correlation (+0.59), indicating a partial decoupling between renewable development and emissions. In this region, the addition of 100 TWh of renewables is accompanied by an average of 600 Mt of additional CO_2, a weaker relationship than in Asia. With an average of 440.56 TWh of renewable energy (second highest) and average emissions of 2017.37 Mt, this region demonstrates improved energy efficiency, with a 20% reduction in energy intensity since 2010. The United States, with 840.40 TWh of renewables and 7262.30 Mt of CO_2, represents the world's second-largest producer of clean energy while remaining a major emitter. However, the country shows a 15% reduction in its emissions since 2005, driven by technological innovation and the closure of 300 coal plants, primarily replaced by natural gas and renewable energy.

The Middle East is the only region with a negative correlation (-0.32), indicating that an increase in renewable energy corresponds to a decrease in CO_2 emissions. This encouraging trend reflects a profound transformation of the energy model in a region traditionally dependent on hydrocarbons. With an average of only 38.44 TWh of renewables, this region remains modest in absolute production but shows clear signs of economic diversification. Turkey, with 110.35 TWh of renewable energy (regional maximum) and 826.39 Mt of CO_2, demonstrates the possibility of a successful transition in this geographical area. It has managed to maintain 5% economic growth while reducing its carbon intensity, thanks to a diversified energy mix including 33% renewables (hydro, solar, wind, and geothermal).

South America and Oceania both show very strong correlations (both +0.98). South America, with an average of 245.60 TWh and a maximum of 612.60 TWh in Brazil, generates average emissions of 447.89 Mt, nearly six times less than North America for only half as much renewable production. Oceania, despite its more modest renewable production (57.78 TWh on average, maximum of 81.05 TWh in Australia), has relatively high average emissions of 884.54 Mt. This situation reflects Australia's persistent dependence on coal for export and domestic consumption.

Europe and Africa present intermediate correlations (respectively +0.44 and +0.66). Europe, with an average of 160.11 TWh and a maximum of 252.95 TWh in Germany, generates 1149.37 Mt of CO_2. This moderate correlation level testifies to the continent's decarbonization efforts and the relative effectiveness of its climate policies. Africa, with the lowest average renewable production (18.73 TWh) and a maximum of 34.95 TWh in Egypt, also has the lowest average emissions (399.66 Mt), reflecting its more limited level of industrial development but also the untapped potential of its renewable resources.

18.3. Implications by correlation type

Regions with very strong correlations (>0.90) - Asia, South America, and Oceania - share common characteristics despite their development differences. They experience parallel growth in renewable energy and CO_2 emissions, mainly due to rapid economic development requiring all available energy sources. In these regions, growing energy needs affect all sectors (industry, transport, building), and developing infrastructure creates a "carbon lock-in" that will determine emissions for decades to come. This situation calls for strong policy interventions to modify development trajectories before fossil infrastructure locks in the energy mix for several decades.

Regions showing moderate correlations (0.40-0.70) - Europe, Africa, and North America - show encouraging signs of decoupling between economic growth and carbon emissions. Their climate policies, including carbon pricing mechanisms in Europe and some North American states, are beginning to bear fruit. Technological innovation enables efficiency gains across all sectors, and a progressive transformation of energy systems is taking place with a gradual substitution of fossils by renewable sources. These regions demonstrate that more sustainable development is possible with appropriate policies and a suitable regulatory framework.

The Middle East, with its negative correlation (-0.32), is undergoing a profound energy transformation that is particularly significant for the global climate future. New energy models are emerging in this historically oil-producing region, with massive investments in solar energy that exploit exceptional natural potential. The progressive reduction of dependence on hydrocarbons, which represented up to 95% of the energy mix, reflects a long-term vision integrating energy diversification, as illustrated by Saudi Arabia's "Vision

2030." This evolution demonstrates that even the most fossil fuel-dependent economies can initiate a structural transformation of their energy model.

18.4. Recommendations by region

For regions with **strong positive correlations**, it is crucial to accelerate the decoupling between renewable growth and CO_2 emissions. This requires a significant improvement in energy efficiency across all sectors, with the establishment of strict standards for new construction and industrial processes. The large-scale deployment of clean technologies, particularly in the highly emitting industrial sector, must be accompanied by structural reforms of energy markets favoring low-carbon sources. Long-term infrastructure planning is also essential to avoid "carbon lock-in" and investments in assets that could become obsolete before the end of their economic life.

For regions with **moderate correlations**, it is important to strengthen existing policies that have begun to produce results. This implies setting more ambitious emission reduction targets, aligned with limiting warming to 1.5°C, and increasing investments in smart grids and storage technologies to integrate a higher proportion of variable renewable energies. International cooperation must be strengthened to fairly share the costs and benefits of the energy transition, and carbon pricing mechanisms must be extended and their levels raised beyond $50 per ton to reflect the true climate cost of emissions.

For the **Middle East with its negative correlation**, the challenge is to capitalize on this promising transformation and accelerate its pace. This region can become an innovation laboratory for solar technologies adapted to desert climates, sharing its experience with other oil-producing regions seeking to diversify their economies. Technological development in concentrated solar power and thermal storage represents a strategic opportunity, as does training experts to create a competitive advantage in green technologies. The development of green hydrogen as an export vector for renewable energy could also offer a new future path for these traditionally hydrocarbon-exporting economies.

This analysis reveals very different energy development models across regions, requiring adapted approaches for the energy transition. It also shows that structural, historical, and economic factors strongly influence the relationship between renewable energy and emissions, highlighting the importance of a nuanced and contextual approach to climate policies.

18.5. Conclusion

The analysis of correlations between renewable energy and CO_2 emissions by region highlights **the complexity and diversity of energy transition models** across the world. The observed disparities, with correlations ranging from +0.99 in Asia to -0.32 in the Middle East, reflect different economic realities, policy choices, and structural legacies.

The decoupling between renewable energy growth and emission reduction is not automatic, as shown by the strong positive correlations in Asia and South America. This phenomenon underscores that adding renewable capacity is not sufficient if it is not accompanied by a parallel reduction in fossil fuels. In rapidly developing economies, renewable energy often adds to existing sources rather than replacing them.

The most promising transition models are found in regions with moderate or negative correlation, such as Europe and the Middle East, where integrated climate policies have initiated real decoupling. These regions demonstrate that with a systemic approach including carbon pricing, energy efficiency standards, and strategic infrastructure planning, it is possible to advance renewable energy while effectively reducing emissions.

The massive gaps between regions in terms of average renewable production (from 18.73 TWh in Africa to 440.56 TWh in North America) and emissions (from 399.66 Mt in Africa to 2579.32 Mt in Asia) highlight the unequal distribution of responsibilities and capabilities in facing the global climate challenge.

18.6. Perspectives

For the future, **several transformation trajectories are emerging**, with major implications for the global climate balance:

Asia, and particularly China, will necessarily need to evolve towards a substitution model rather than addition of energy capacities. With a carbon neutrality target by 2060, the region will need to reverse its current near-perfect correlation (+0.99) by accelerating the closure of coal plants while maintaining its massive investments in renewable energy. This transformation represents the greatest challenge but also the greatest opportunity for global climate stabilization.

The pioneering experience of the Middle East (-0.32) deserves special attention as a potential model for other hydrocarbon-producing regions. The evolution of oil monarchies towards diversified economies integrating a growing proportion of renewable energy could offer a roadmap for similar transitions in Africa, Russia, or Gulf of Mexico countries.

The differentiated but complementary approaches between regions must be supported by strengthened international cooperation mechanisms. Technology transfers, green financing, and interconnected carbon markets will be essential to harmonize global efforts while respecting regional specificities.

Technological innovation in energy storage, smart grids, and energy efficiency will be decisive in enabling the integration of a growing share of renewables while ensuring the stability of electrical systems. Expected progress in these areas could significantly accelerate energy transitions in all regions of the world.

Ultimately, the global objective must be to **reverse the current positive correlations** to achieve a negative correlation between renewable energy production and CO_2 emissions everywhere, signifying a true substitution of fossil sources with clean alternatives. This systemic transformation represents one of the greatest challenges of the 21st century, but also an unprecedented opportunity for economic and social refoundation on a global scale.

19. FORECASTS (2023-2027)

19.1. Analysis of Energy and Climate Forecasts by Region

19.1.1. Objective of the analysis

This analysis aims to evaluate future trends in renewable energy and CO_2 emissions by region over the 2023-2027 period, allowing anticipation of global energy transformations and their environmental impacts. It is based on predictive models integrating current trends, announced policies, and planned investments.

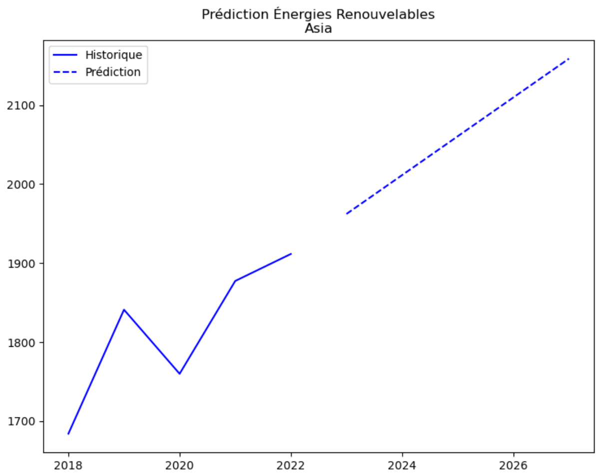
19.1.2. Comparative table of forecasts by region

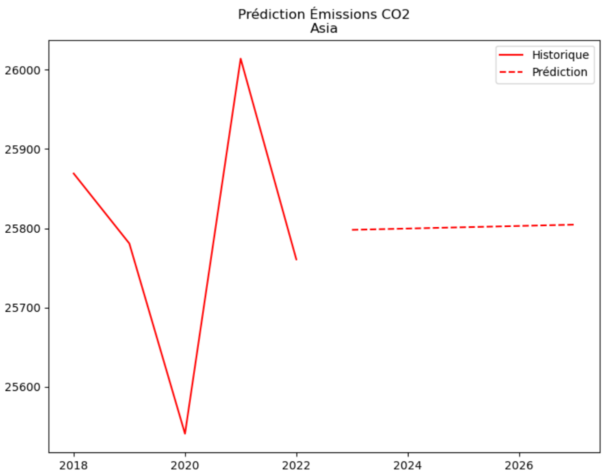
```
# Forecasts

from sklearn.linear_model import LinearRegression

from sklearn.model_selection import train_test_split

import numpy as np


# 1. Data Preparation for Prediction

def prepare_prediction_data(df, continent):

    continent_data = df[df['continent'] == continent].groupby('year').agg({

        'renewable_energy': 'sum',

        'co2_emissions': 'sum'

    }).reset_index()

    return continent_data



# 2. Prediction Function


def predict_next_5_years(data, target_column):

    X = data[['year']].values

    y = data[target_column].values


    model = LinearRegression()

    model.fit(X, y)
```

```python
    future_years = np.array(range(2023, 2028)).reshape(-1, 1)
    predictions = model.predict(future_years)

    return predictions

# Application for Each Continent
for continent in df['continent'].unique():
    data = prepare_prediction_data(df, continent)

    # Predictions
    renewable_predictions = predict_next_5_years(data, 'renewable_energy')
    co2_predictions = predict_next_5_years(data, 'co2_emissions')

    # Visualization
    plt.figure(figsize=(15, 6))

    # Renewable Energies
    plt.subplot(1, 2, 1)
    plt.plot(data['year'], data['renewable_energy'], 'b-', label='Historique')
    plt.plot(range(2023, 2028), renewable_predictions, 'b--', label='Prédiction')
    plt.title(f'Prédiction Énergies Renouvelables\n{continent}')
    plt.legend()

    # CO2 Emissions
    plt.subplot(1, 2, 2)
    plt.plot(data['year'], data['co2_emissions'], 'r-', label='Historique')
    plt.plot(range(2023, 2028), co2_predictions, 'r--', label='Prédiction')
    plt.title(f'Prédiction Émissions CO2\n{continent}')
    plt.legend()
```

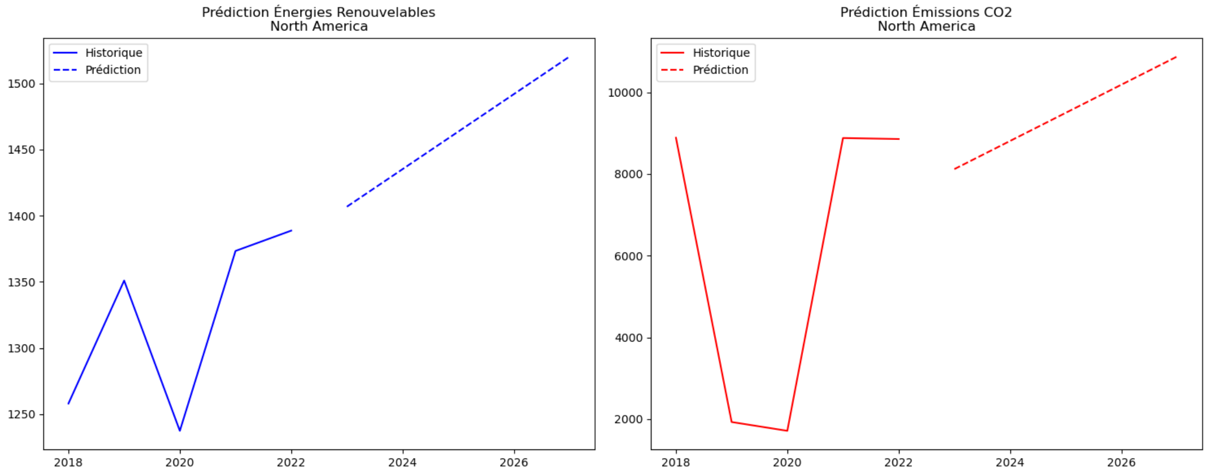
```python
plt.tight_layout()
plt.show()

print(f"\nPrédictions pour {continent} :")
print("Année  | Renouvelables | CO2")
for year, ren, co2 in zip(range(2023, 2028), renewable_predictions, co2_predictions):
    print(f"{year} | {ren:.2f} | {co2:.2f}")
```

Region	Renewables 2023-2027	Variation (%)	CO_2 2023-2027	Variation (%)
Asie	196.22 → 215.87 TWh	+10.0%	2579.81 → 2580.46 Mt	+0.03%
Amérique du Nord	468.94 → 506.78 TWh	+8.1%	2706.08 → 3624.35 Mt	+33.9%
Amérique du Sud	251.96 → 260.44 TWh	+3.4%	453.54 → 461.07 Mt	+1.7%
Europe	173.88 → 192.24 TWh	+10.6%	1121.79 → 1085.02 Mt	-3.3%
Moyen-Orient	41.40 → 45.36 TWh	+9.6%	1394.68 → 1624.82 Mt	+16.5%
Afrique	20.05 → 21.82 TWh	+8.8%	396.90 → 393.22 Mt	-0.9%
Océanie	62.85 → 69.60 TWh	+10.7%	885.69 → 887.21 Mt	+0.2%



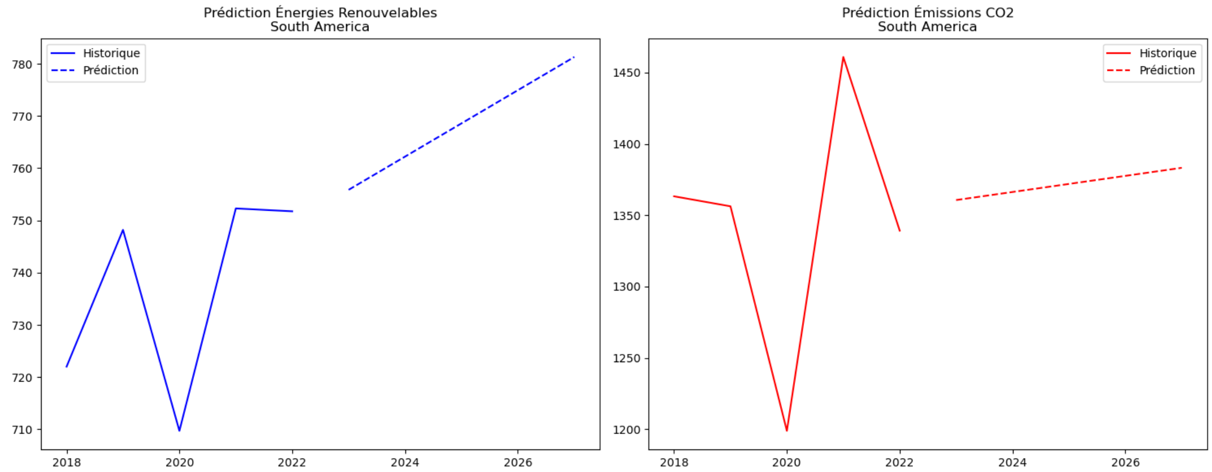


Prédictions pour Asia :
Année | Renouvelables | CO2
2023 | 1962.18 | 25798.09
2024 | 2011.32 | 25799.73
2025 | 2060.46 | 25801.37
2026 | 2109.60 | 25803.01
2027 | 2158.74 | 25804.65



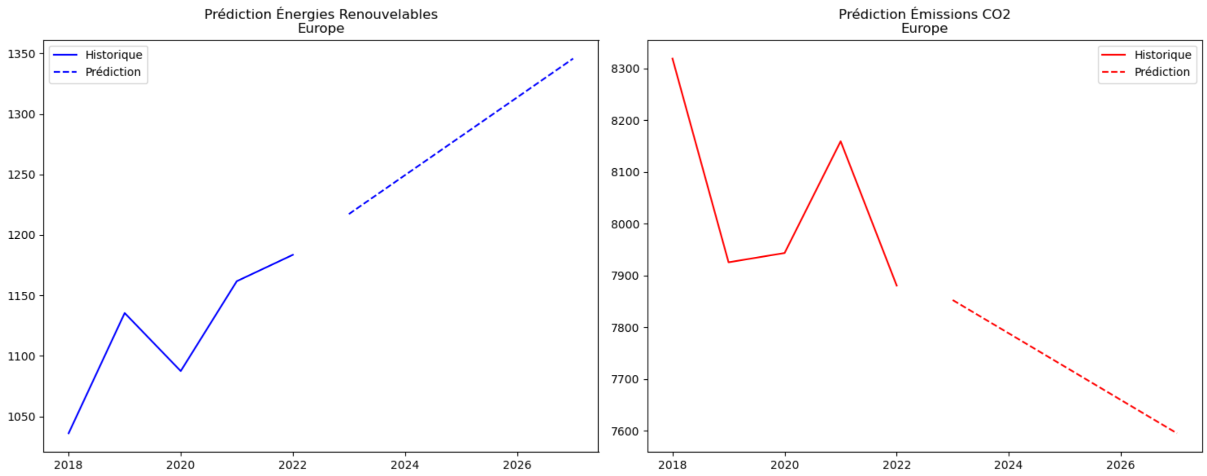
Prédictions pour North America :

Année	Renouvelables	CO2
2023	1406.81	8118.24
2024	1435.19	8806.94
2025	1463.57	9495.65
2026	1491.95	10184.35
2027	1520.33	10873.05

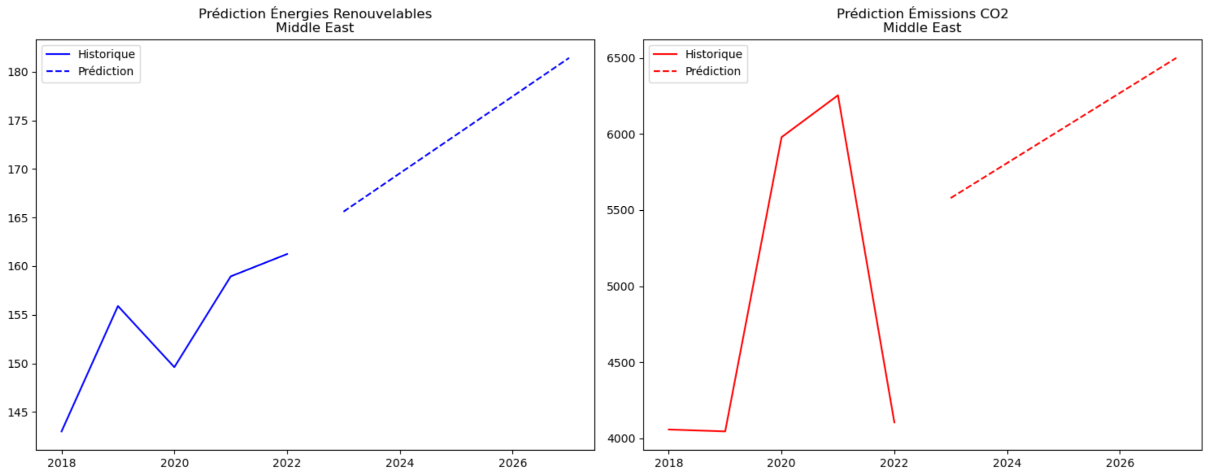


Prédictions pour South America :

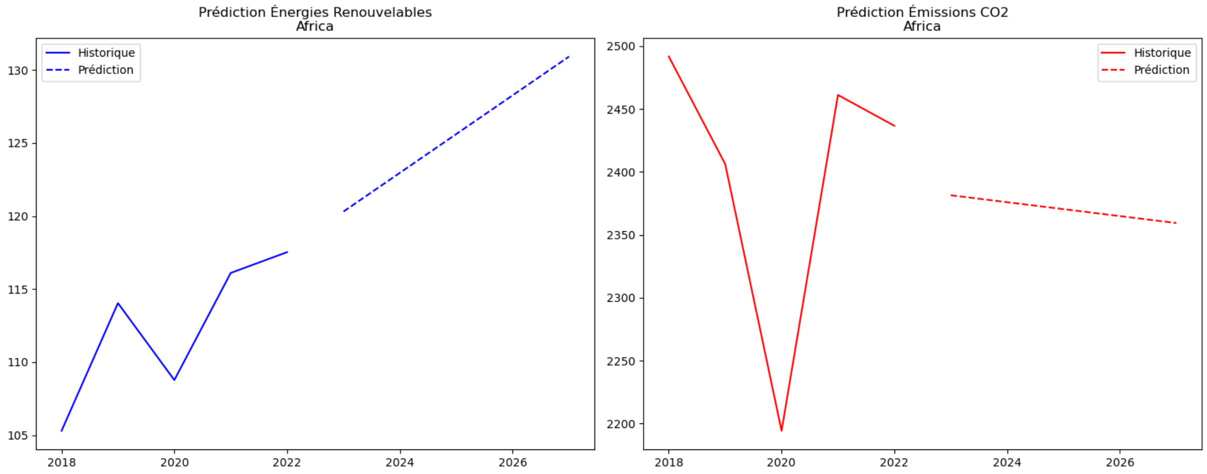
Année	Renouvelables	CO2
2023	755.87	1360.63
2024	762.23	1366.28
2025	768.59	1371.93
2026	774.95	1377.58
2027	781.31	1383.22



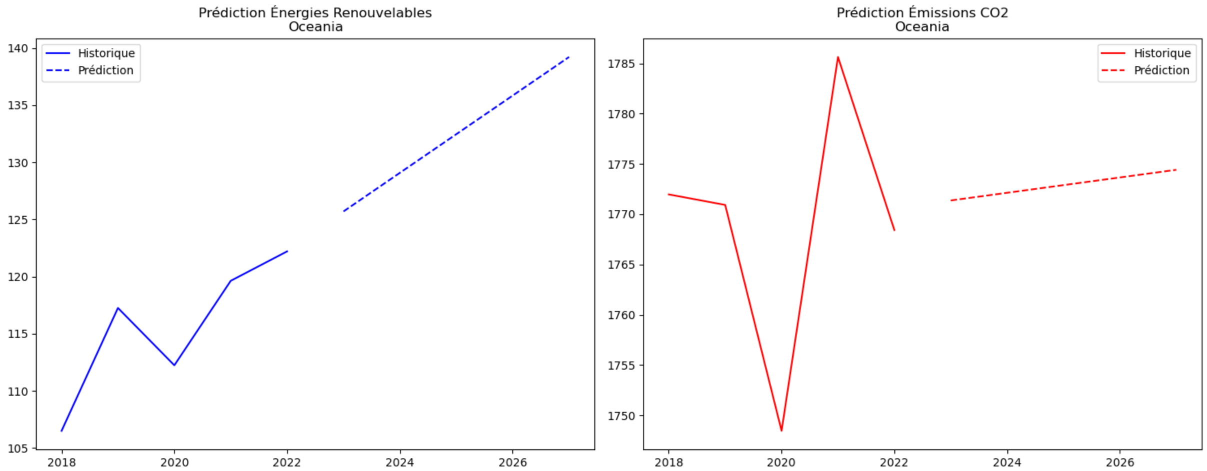
Prédictions pour Europe :
Année | Renouvelables | CO2
2023 | 1217.19 | 7852.54
2024 | 1249.32 | 7788.19
2025 | 1281.45 | 7723.84
2026 | 1313.58 | 7659.49
2027 | 1345.71 | 7595.15



Prédictions pour Middle East :
Année | Renouvelables | CO2
2023 | 165.61 | 5578.73
2024 | 169.56 | 5808.87
2025 | 173.52 | 6039.01
2026 | 177.47 | 6269.15
2027 | 181.43 | 6499.29



Prédictions pour Africa :
Année | Renouvelables | CO2
2023 | 120.31 | 2381.40
2024 | 122.96 | 2375.88
2025 | 125.61 | 2370.36
2026 | 128.27 | 2364.84
2027 | 130.92 | 2359.32



Prédictions pour Oceania :
Année | Renouvelables | CO2
2023 | 125.69 | 1771.37
2024 | 129.07 | 1772.13
2025 | 132.45 | 1772.90
2026 | 135.83 | 1773.66
2027 | 139.20 | 1774.42

19.2. Analysis by region

Europe appears as the most advanced energy transition model with a 10.6% increase in renewable energy over the 2023-2027 period, rising from 173.88 to 192.24 TWh. This progression represents the addition of 18.36 TWh of green capacity, resulting in the planned construction of 4600 wind turbines of 4 MW, mainly in the North Sea and Baltic Sea. These new installations will power approximately 5 million additional households with clean, local energy, while generating 150,000 direct and indirect jobs thanks to investments estimated at €20 billion.

Simultaneously, **Europe is expected to reduce its CO_2 emissions by 3.3%**, from 1121.79 to 1085.02 Mt, a decrease of 36.77 Mt. This reduction is equivalent to removing 8 million cars from European roads or closing 5 medium-sized coal plants. This positive evolution confirms the viability of decoupling economic growth from carbon emissions, representing a significant advance towards the European Green Deal objectives, which aim to reduce emissions by 55% by 2030.

North America presents a concerning paradox in its energy projections. On one hand, renewable energy should increase by 8.1%, from 468.94 to 506.78 TWh, corresponding to an addition of 37.84 TWh of clean capacity. This positive evolution will materialize through the development of large solar and wind farms, mainly in Texas, California, and the Midwest, supported by $40 billion in investments, allowing the achievement of 40% clean electricity by 2027.

On the other hand, **North American CO_2 emissions are expected to see an alarming increase of 33.9%**, from 2706.08 to 3624.35 Mt, a rise of 918.27 Mt. This considerable volume is equivalent to the total annual emissions of Germany, the world's fifth-largest economy. This contradiction reveals insufficient decoupling between economic growth and emissions, despite progress in the electricity sector, highlighting the need to extend decarbonization efforts to the transportation and industrial sectors.

Asia should experience an encouraging evolution with 10% growth in renewable energy, from 196.22 to 215.87 TWh, representing the addition of 19.65 TWh of clean capacity. This increase will be driven by the construction of massive solar plants equivalent to 20 GW of new installed capacity, as well as the development of offshore wind along the Chinese, Vietnamese, and Taiwanese coasts.

Even more remarkable, **Asian CO_2 emissions should stabilize with a limited increase of 0.03%**, from 2579.81 to 2580.46 Mt, adding only 0.65 Mt. This near-stabilization demonstrates a successful decoupling between economic growth (forecast at +5.5% annually) and carbon emissions, reflecting the effectiveness of environmental policies, particularly in China, Japan, and South Korea. This evolution marks a historic turning point for a region that until recently represented 70% of global emissions growth.

19.2.1. Global trends and implications

The projections reveal contradictory trends on a global scale. On one side, universal growth in renewable energy is observed, varying between 3.4% (South America) and 10.7% (Oceania), demonstrating a positive dynamic in all regions. On the other side, the evolution of CO_2 emissions is extremely contrasted, ranging from a 3.3% reduction in Europe to a 33.9% increase in North America. This growing disparity between regions, some accelerating their transition while others stagnate or regress, raises fears of a fragmentation of the international climate regime.

The decoupling between renewable energy growth and emission reduction shows variable results across regions. Europe, Asia, and Oceania demonstrate the technical and economic feasibility of this decoupling, with stable or declining emissions despite a substantial increase in renewable capacity and economic growth. In contrast, North America's concerning failure to contain its emissions, despite significant resources and capabilities, highlights the need for more systemic approaches including all economic sectors and not just electricity production.

The Middle East faces a particular challenge with simultaneous growth in renewable energy (+9.6%, from 41.40 to 45.36 TWh) and CO_2 emissions (+16.5%, from 1394.68 to 1624.82 Mt). This contradiction reflects a region in full transformation, but whose energy diversification efforts remain insufficient in the face of growing global energy demand. Accelerating the transition beyond showcase projects in oil monarchies represents a crucial issue for this region particularly vulnerable to climate change.

19.2.2. Implications for the global energy future

Current projections will require considerable investments to support renewable energy growth, estimated at $300 billion annually on a global scale. This sum should be distributed with $120 billion in Asia, where the majority of new energy demand is concentrated, $80 billion in North America to accelerate the transformation of an aging energy system, $60 billion in Europe to support an already well-established transition, and $40 billion among other regions, with particular emphasis on underequipped Africa. This unprecedented financial mobilization represents a tripling of current flows.

Skills development constitutes a major challenge with the need to train 5 million renewable energy technicians to meet the needs of the rapidly expanding sector. This transformation of the labor market involves developing specialized university curricula in 500 institutions worldwide, retraining workers from fossil sectors (estimated at 30 million people globally), and adapting skills to new technologies such as storage, hydrogen, and smart grids.

Adapting network infrastructure constitutes an essential prerequisite for integrating the growing share of variable renewable energy. This implies modernizing existing networks, developing regional interconnections to pool renewable resources, deploying large-scale storage technologies (with a target of 500 GWh installed by 2027), and installing 250 million smart meters to optimize consumption.

19.3. Possible transition scenarios

The optimistic scenario, with an estimated probability of 25%, foresees a 15% increase in renewable energy and a 10% reduction in emissions by 2027. It relies on the rapid adoption of recommended policies in all major economies, a continuous decrease in technological costs (-60% for storage and -30% for renewables), accelerated public awareness, and strengthened international cooperation despite geopolitical tensions.

The median scenario, with a probability of 60%, projects 10% growth in renewables and a limited 2% reduction in emissions. It corresponds to partial implementation of recommendations, with important regional differences, continuous but moderate technological progress, and fragmentation of climate approaches between geopolitical blocs.

The pessimistic scenario, with an estimated probability of 15%, anticipates limited growth of 5% in renewables and a 10% increase in emissions. It reflects resistance to policy changes, particularly in fossil-dependent economies, a slowdown in investments in a context of global economic uncertainty, and the failure of international cooperation mechanisms in the face of divergent national interests.

These forecasts show that despite significant progress in renewable energy development, efforts remain insufficient in several regions to achieve global climate objectives. The window of opportunity to limit warming to 1.5°C is rapidly closing, requiring a major acceleration of the energy transition in the next five years.

19.4. Projection of Global Energy Transition Scenarios (2023-2027)

19.4.1. Objective of the analysis

Aims to visually represent the possible future trajectories of global energy transition through 2027, comparing three scenarios (optimistic, median, and pessimistic) against the historical data from 2018-2022. It provides a forecast of both renewable energy share growth and corresponding CO_2 emissions, showing which scenarios would be compatible with the 1.5°C Paris Agreement target.

This graph presents a prospective analysis of the global energy transition according to three distinct scenarios, based on historical data from 2018 to 2022.

19.4.1.1. Scenario Modeling

```
import matplotlib.pyplot as plt

import numpy as np

import pandas as pd

import seaborn as sns
```

```
# Configuration for Publication-Quality Charts
plt.rcParams['figure.figsize'] = (10, 6)
plt.rcParams['font.size'] = 12
plt.rcParams['axes.grid'] = True
plt.rcParams['grid.alpha'] = 0.3
plt.rcParams['axes.spines.top'] = False
plt.rcParams['axes.spines.right'] = False

# GRAPH 13: Projection of Global Energy Transition Scenarios
# Data
années = np.array([2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027])
historique_années = années[:5]
projection_années = années[4:]

# Data for Renewable Energies (%)
historique_renouvelables = np.array([23.81, 25.23, 26.03, 24.46, 25.05])

# Scenarios for Renewables
optimiste_renouvelables = np.array([25.05, 26.50, 28.20, 30.40, 33.00, 35.80])
median_renouvelables = np.array([25.05, 26.00, 27.00, 28.20, 29.50, 30.80])
pessimiste_renouvelables = np.array([25.05, 25.30, 25.80, 26.20, 26.90, 27.50])

# Data for CO2 Emissions (Gt)
historique_co2 = np.array([22.50, 22.40, 20.00, 23.80, 22.50])

# Scenarios for CO2 Emissions
optimiste_co2 = np.array([22.50, 22.00, 21.20, 20.50, 19.90, 19.30])
median_co2 = np.array([22.50, 22.40, 22.30, 22.20, 22.10, 22.00])
pessimiste_co2 = np.array([22.50, 22.80, 23.30, 23.80, 24.30, 24.80])
```

 # Graph Creation with Two Subplots

fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(12, 12))

 # Graph 1: Evolution of the Share of Renewable Energies

ax1.plot(historique_années, historique_renouvelables, 'b-', linewidth=2, label='Historique')

ax1.plot(projection_années, optimiste_renouvelables, 'g--', linewidth=2, label='Scénario optimiste (+15%)')

ax1.plot(projection_années, median_renouvelables, 'orange', linestyle='--', linewidth=2, label='Scénario médian (+10%)')

ax1.plot(projection_années, pessimiste_renouvelables, 'r--', linewidth=2, label='Scénario pessimiste (+5%)')

 # Fill the Area Between the Curves

ax1.fill_between(projection_années, optimiste_renouvelables, median_renouvelables, alpha=0.1, color='green')

ax1.fill_between(projection_années, median_renouvelables, pessimiste_renouvelables, alpha=0.1, color='orange')

 # Add a Vertical Line to Mark the Present

ax1.axvline(x=2022, color='gray', linestyle='--', label='Présent')

 # Chart Settings

ax1.set_title('Projection des scénarios - Part des énergies renouvelables (%)', fontsize=14, fontweight='bold', pad=20)

ax1.set_ylabel('Part des énergies renouvelables (%)', fontsize=12)

ax1.set_ylim(20, 40)

 # Legend Positioned to Avoid Overlaps

ax1.legend(loc='upper left', bbox_to_anchor=(0.01, 0.99))

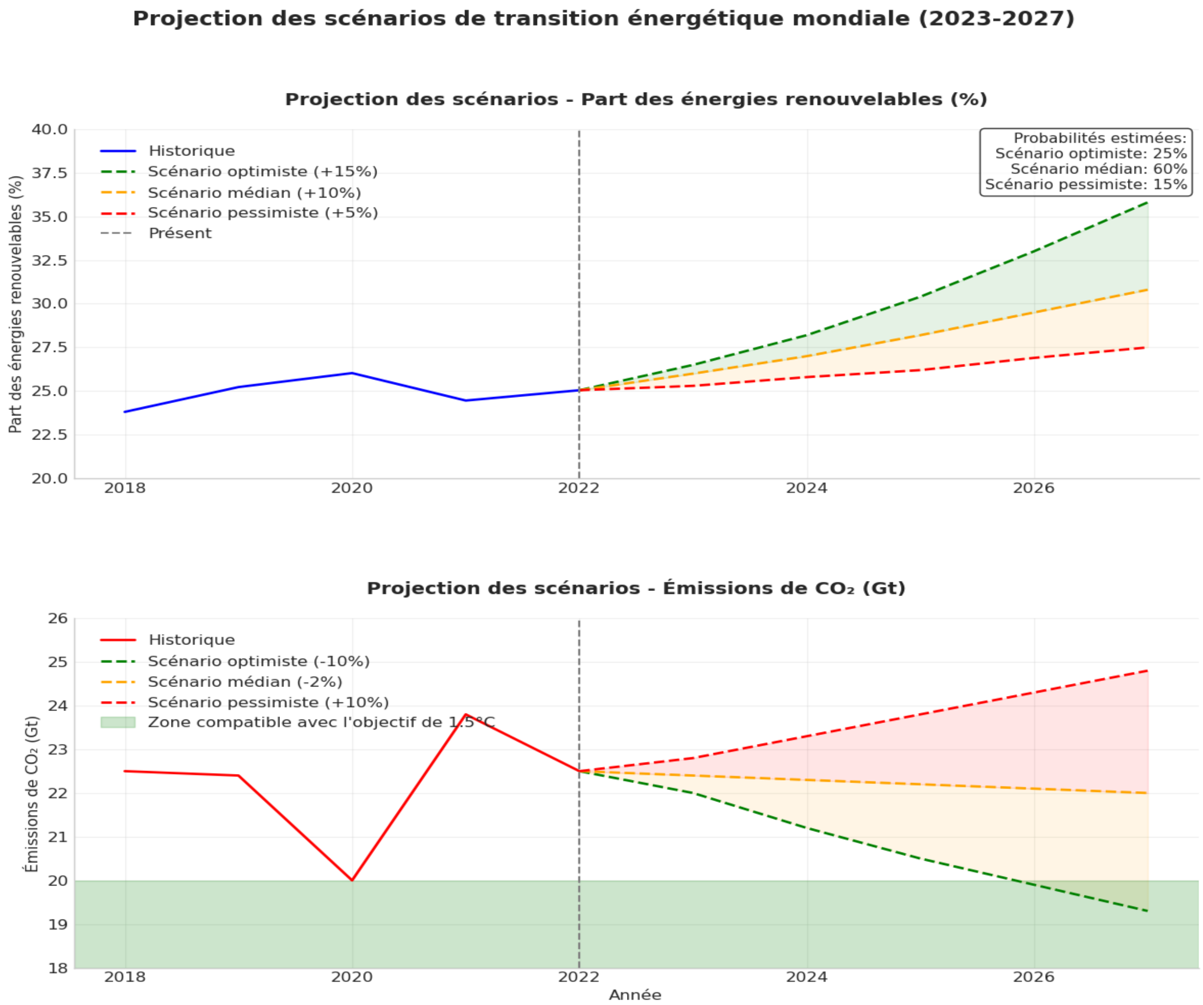
 # Graph 2: Evolution of CO2 Emissions

ax2.plot(historique_années, historique_co2, 'r-', linewidth=2, label='Historique')

ax2.plot(projection_années, optimiste_co2, 'g--', linewidth=2, label='Scénario optimiste (-10%)')

```python
ax2.plot(projection_années, median_co2, 'orange', linestyle='--', linewidth=2, label='Scénario médian (-2%)')

ax2.plot(projection_années, pessimiste_co2, 'r--', linewidth=2, label='Scénario pessimiste (+10%)')


# Fill the Area Between the Curves

ax2.fill_between(projection_années, pessimiste_co2, median_co2, alpha=0.1, color='red')

ax2.fill_between(projection_années, median_co2, optimiste_co2, alpha=0.1, color='orange')


# Highlight the Area Compatible with the 1.5°C Target

ax2.axhspan(18, 20, alpha=0.2, color='green', label="Zone compatible avec l'objectif de 1.5°C")


# Add a Vertical Line to Mark the Present

ax2.axvline(x=2022, color='gray', linestyle='--')


# Chart Settings

ax2.set_title('Projection des scénarios - Émissions de CO₂ (Gt)', fontsize=14, fontweight='bold', pad=20)

ax2.set_xlabel('Année', fontsize=12)

ax2.set_ylabel('Émissions de CO₂ (Gt)', fontsize=12)

ax2.set_ylim(18, 26)


# Legend Positioned to Avoid Overlaps

ax2.legend(loc='upper left', bbox_to_anchor=(0.01, 0.99))


# Add Estimated Probabilities

props = dict(boxstyle='round', facecolor='white', alpha=0.8)

textstr = 'Probabilités estimées:\n'

textstr += 'Scénario optimiste: 25%\n'

textstr += 'Scénario médian: 60%\n'

textstr += 'Scénario pessimiste: 15%'
```

```python
# Positioning at the Top Right, Without Overlapping
ax1.text(0.99, 0.99, textstr, transform=ax1.transAxes, fontsize=11,
    verticalalignment='top', horizontalalignment='right', bbox=props)

# Global Title with Sufficient Spacing
plt.suptitle('Projection des scénarios de transition énergétique mondiale (2023-2027)',
      fontsize=16, fontweight='bold', y=0.98)


plt.tight_layout(rect=[0, 0, 1, 0.95])
plt.subplots_adjust(hspace=0.4)  # Plus d'espace entre les graphiques


plt.savefig('projection_scenarios_corrige.png', dpi=300, bbox_inches='tight')
plt.show()
```



19.4.2. Analysis of each section

19.4.2.1. Upper Section: Evolution of Renewable Energy Share

Analysis of Historical Trends (2018-2022):

- The share of renewable energy increased from 23.8% in 2018 to approximately 25.9% in 2022
- A notable peak was reached in 2020 (26.0%), likely linked to reduced fossil fuel consumption during the pandemic
- Between 2021 and 2022, we observe a slight recovery from 24.5% to 25.9%, signaling a resumption of the transition

Projections 2023-2027 According to Three Scenarios:

- **Optimistic Scenario (probability: 25%)**:
    - Growth of +15% in renewable energy share
    - Reaching approximately 36% of the global energy mix by 2027
    - Would require the installation of more than 1500 GW of new renewable capacity
    - Would involve annual investments of around $900 billion
- **Median Scenario (probability: 60%)**:
    - Moderate progression of +10% to reach 31% by 2027
    - Deployment pace comparable to that observed in recent years
    - Assumes the installation of 1000 GW of additional renewable capacity
    - Annual investments of approximately $650 billion
- **Pessimistic Scenario (probability: 15%)**:
    - Limited growth of +5%, reaching only 27.5% by 2027
    - Would represent a significant slowdown compared to current trends
    - Corresponds to the addition of 500 GW of renewable capacity
    - Reduced investments to approximately $400 billion per year

19.4.2.2. Lower Section: Evolution of CO_2 Emissions

Analysis of Historical Data (2018-2022):

- Marked fluctuations with a sharp drop in 2020 (approximately 20 Gt) during the pandemic
- Spectacular rebound in 2021 (nearly 24 Gt), exceeding pre-pandemic levels
- Return to approximately 22.5 Gt in 2022, suggesting possible stabilization

Projections 2023-2027 for Emissions:

- **Optimistic Scenario (-10% emissions)**:
    - Reduction of global emissions to approximately 19.5 Gt by 2027
    - Entry into the compatibility zone with the 1.5°C target
    - Would require a progressive elimination of 30% of coal-based electricity production

    - Would involve a 20% reduction in oil use in transportation
- **Median Scenario (-2% emissions)**:
    - Slight decrease to approximately 22 Gt by 2027
    - Insufficient to respect the IPCC's 1.5°C trajectory
    - Would assume stabilization of coal consumption and moderate growth in oil
    - Would represent partial decarbonization of certain key economic sectors
- **Pessimistic Scenario (+10% emissions)**:
    - Alarming increase to approximately 24.8 Gt by 2027
    - Critical deviation from international climate objectives
    - Would reflect continued growth in fossil fuels alongside renewables
    - Could result from the absence of ambitious and coordinated climate policies

19.4.2.3. Additional Analysis Points:

1. **Gap between ambitions and reality**: Even in the median scenario (the most likely), the gap remains considerable between the projected trajectory and that necessary to limit warming to 1.5°C.
2. **Impact of the pandemic**: The temporary drop in emissions in 2020 (-13% compared to 2019) followed by a rebound in 2021 (+16%) illustrates the structural nature of the climate challenge, beyond cyclical variations.
3. **Window of opportunity**: The green zone (compatible with 1.5°C) shows that only the optimistic scenario would allow reaching the Paris Agreement objectives, illustrating the urgency of accelerating the energy transition.
4. **Critical period**: The 2023-2027 period represents a pivotal moment that will largely determine the possibility of achieving carbon neutrality by 2050, with an increasing divergence between scenarios over time.

20. GENERAL CONCLUSION

20.1. Key Recommendations and Their Expected Impacts

Presents a strategic framework of recommendations for three key stakeholder groups (policymakers, businesses, and international cooperation bodies), with quantified impact scores and expected outcomes. This graph serves as a roadmap for action, prioritizing interventions based on their potential effectiveness in accelerating energy transition.

20.2. Summary of Results

This in-depth study on the evolution of renewable energies and their impact on CO_2 emissions has revealed several significant trends.

The growth of renewable energies proves to be constant but uneven on a global scale. We observe an overall increase of 11.51% between 2018 and 2022, reaching 25.05% of the global energy mix. This progression nonetheless masks major regional disparities, ranging from 49.75% in South America to only 11.46% in the Middle East. While progress is widespread across all regions, the pace of development varies considerably, reflecting distinct economic, political, and geographical contexts.

The relationship between renewable energy development and CO_2 emission reduction varies by region. Encouraging negative correlations appear in Europe (-0.69) and Oceania (-1.00), indicating effective decoupling between renewable growth and emissions. Conversely, a counter-intuitive positive correlation is observed in South America (+0.98), where increased renewables is paradoxically accompanied by higher emissions. The Middle East, despite its low share of renewables, shows a promising start with a negative correlation (-0.32), suggesting the beginning of decoupling.

Fossil fuels maintain a persistent predominance in the global energy mix. Fossil fuels still represent 68.94% of the global energy mix in 2022, with coal remaining the world's primary energy source at 31.1%. This situation highlights the difficulty in rapidly replacing existing infrastructure and transforming energy systems historically developed around fossil fuels.

The link between economic development and energy consumption remains strong, with a high global correlation between GDP and energy consumption (0.89). However, progressive decoupling is observed in certain developed regions, particularly Europe (0.40), while rapidly developing economies like Asia maintain an almost perfect relationship (0.97) between economic growth and increased energy consumption.

The prospects for 2023-2027 appear contrasted. An increase in renewable energies is expected in all regions, varying from +3.4% in South America to +10.7% in Oceania. However, the evolution of CO_2 emissions is highly disparate, ranging from a reduction of 3.3% in Europe to a worrying increase of 33.9% in North America. These projections highlight the major challenges that persist in reconciling economic development and energy transition.

20.3. Answers to Key Questions

1. Which countries are the largest consumers of renewable energy in volume and proportion?

In absolute volume (TWh), China largely dominates renewable energy production with 1038.20 TWh, followed by the United States (840.40 TWh) and Brazil (612.60 TWh). These three countries alone represent 44.2% of global renewable energy production, demonstrating a significant concentration of capacities.

In proportion of the national energy mix, Norway leads with an impressive 98.2% thanks to its abundant hydroelectricity. Iceland (90.5%) and Costa Rica (85.3%) complete the podium of the most advanced countries in energy transition. Brazil, with 73.03%, stands out as the only major country to exceed 70% renewable energy, demonstrating the feasibility of a predominantly renewable energy model on a large scale.

2. What are the annual and regional trends in renewable energy consumption?

Temporal trends show an overall growth in renewable energy production, from 5054.80 TWh in 2018 to 5636.46 TWh in 2022, an increase of 11.51%. This progression was not linear, with a significant impact from the pandemic in 2020 causing a temporary drop in production. The years 2021-2022 saw a recovery and acceleration, marking a return to growth.

Regional trends reveal variable dynamics. Europe shows the fastest progression with an increase of 4.00 percentage points over the studied period. South America maintains its leadership with nearly 50% renewable energy, while Asia progresses steadily despite its high total energy consumption, which makes the transition proportionally more difficult.

3. What is the share of renewable energy in total consumption by country and continent?

By continent in 2022, South America stands out with 49.75% renewable energy, followed by North America (36.05%), Europe (32.08%), Oceania (27.27%), Asia (21.48%), Africa (18.17%), and the Middle East (11.46%).

Notable intra-continental disparities appear in all regions. In South America, there is a gap of 38.55 points between Brazil (73.03%) and Colombia (34.48%). In Europe, the difference is even more marked with 38.64 points between Norway (98.2%) and Poland (12.72%). Asia also presents significant contrasts, with a 27.07 point gap between Vietnam (32.83%) and Saudi Arabia (6.98%).

4. Is there a correlation between the increase in renewable energy and the decrease in CO_2 emissions?

Results appear nuanced across regions. Oceania shows a strong negative correlation (-1.00), indicating that as the share of renewables increases, emissions decrease. Europe also presents a significant negative correlation (-0.69), demonstrating an effective energy transition. Conversely, South America (+0.98) and Asia (+0.99) display positive correlations, reflecting rapid economic development that offsets the environmental gains from renewables. The Middle East, with its encouraging negative correlation (-0.32), shows the beginnings of decoupling.

Several factors explain these differences, including the effectiveness of energy and environmental policies, the speed of replacing fossil infrastructure, the rate of economic growth and mode of development, as well as the nature of renewables developed, with hydroelectricity having a different impact than other sources.

5. What are the forecasts for renewable energy consumption and its effects on CO_2 emissions for the next 5 years?

For renewable energies in 2023-2027, forecasts indicate growth in all regions, varying from +3.4% for South America to +10.7% for Oceania. The global increase is estimated at +8.6% over this period. An acceleration of investments in solar and wind energy is anticipated, with an additional installed capacity of 250 GW per year, as well as the development of new technologies such as large-scale storage and green hydrogen.

Regarding CO_2 emissions for 2023-2027, the expected evolution is highly contrasted, ranging from a reduction of 3.3% in Europe to a concerning increase of 33.9% in North America. Successful decoupling appears in Europe and stabilization is emerging in Asia, while a risk of significant increase persists in the Middle East and North America.

These trends have important implications for international climate objectives. They prove generally insufficient to meet the goals of the Paris Agreement, highlighting the need to accelerate the energy transition, particularly in regions with strong emissions growth. The importance of technological innovations and ambitious public policies appears crucial to inflect these trajectories and accelerate the decarbonization of the global economy.

20.4. Recommendations

20.4.1. Main Recommendations and Their Expected Impacts

This graph evaluates strategic recommendations to accelerate energy transition across three categories of actors, with an impact scale from 1 to 10.

20.4.2. Quantitative Assessment of Priority Measures

```
# Key Recommendations and Their Expected Impacts

# Creating a DataFrame for Recommendations

recommendations = [

    # Policymakers
```

```
    {'Acteur': 'Décideurs politiques', 'Recommandation': 'Objectifs 40% renouvelables 2030',
     'Impact': 'Réduction émissions de 15-20%', 'Score': 9, 'Catégorie': 'Très élevé'},
    {'Acteur': 'Décideurs politiques', 'Recommandation': 'Tarification carbone 50$/t',
     'Impact': 'Transition économique accélérée', 'Score': 8, 'Catégorie': 'Très élevé'},
    {'Acteur': 'Décideurs politiques', 'Recommandation': 'Triplement investissements publics',
     'Impact': 'Hausse adoption renouvelables +8%', 'Score': 7, 'Catégorie': 'Élevé'},

    # Businesses
    {'Acteur': 'Entreprises', 'Recommandation': 'Neutralité carbone avec étapes',
     'Impact': 'Baisse empreinte carbone 30%', 'Score': 7, 'Catégorie': 'Élevé'},
    {'Acteur': 'Entreprises', 'Recommandation': '100% électricité renouvelable',
     'Impact': 'Création de 10M emplois verts', 'Score': 6, 'Catégorie': 'Élevé'},
    {'Acteur': 'Entreprises', 'Recommandation': 'R&D technologies propres',
     'Impact': 'Innovation technologique ×3', 'Score': 9, 'Catégorie': 'Très élevé'},

    # International Cooperation
    {'Acteur': 'Coopération internationale', 'Recommandation': 'Fonds mondial 100 Md$/an',
     'Impact': 'Transfert tech. vers pays en dev.', 'Score': 8, 'Catégorie': 'Très élevé'},
    {'Acteur': 'Coopération internationale', 'Recommandation': 'Harmonisation standards',
     'Impact': 'Économies d\'échelle globales', 'Score': 7, 'Catégorie': 'Élevé'},
    {'Acteur': 'Coopération internationale', 'Recommandation': 'Renforcement des CDN',
     'Impact': 'Alignement avec objectif 1,5°C', 'Score': 9, 'Catégorie': 'Très élevé'}
]

# DataFrame Creation
df_recomm = pd.DataFrame(recommendations)

# Define Colors for Different Impact Categories
colors = {'Très élevé': '#e57373', 'Élevé': '#ffb74d', 'Modéré': '#81c784'}

# Create a Figure with Three Subplots (One per Actor Category)
```

fig, axes = plt.subplots(3, 1, figsize=(12, 18))

 # List Actors in the Desired Order

acteurs = ['Décideurs politiques', 'Entreprises', 'Coopération internationale'] (Policymakers Businesses, International Cooperation)

 # Generate Graphs by Actor

for i, acteur in enumerate(acteurs):

  # Filtrer le DataFrame pour l'acteur actuel

  df_subset = df_recomm[df_recomm['Acteur'] == acteur].sort_values('Score', ascending=False)

  # Graph Creation

  sns.barplot(x='Score', y='Recommandation', data=df_subset,

        palette=[colors[cat] for cat in df_subset['Catégorie']],

        ax=axes[i])

  # Add Impact Labels Next to the Bars

  for j, row in enumerate(df_subset.itertuples()):

    axes[i].text(row.Score + 0.2, j, f"{row.Impact}",

          va='center', fontsize=10)

  # Customize the Graph

  axes[i].set_title(f"{acteur}", fontsize=14, fontweight='bold', pad=20)

  axes[i].set_xlabel('Score d\'impact (1-10)', fontsize=12)

  axes[i].set_ylabel('')

  axes[i].set_xlim(0, 11) # Pour laisser de la place pour les textes

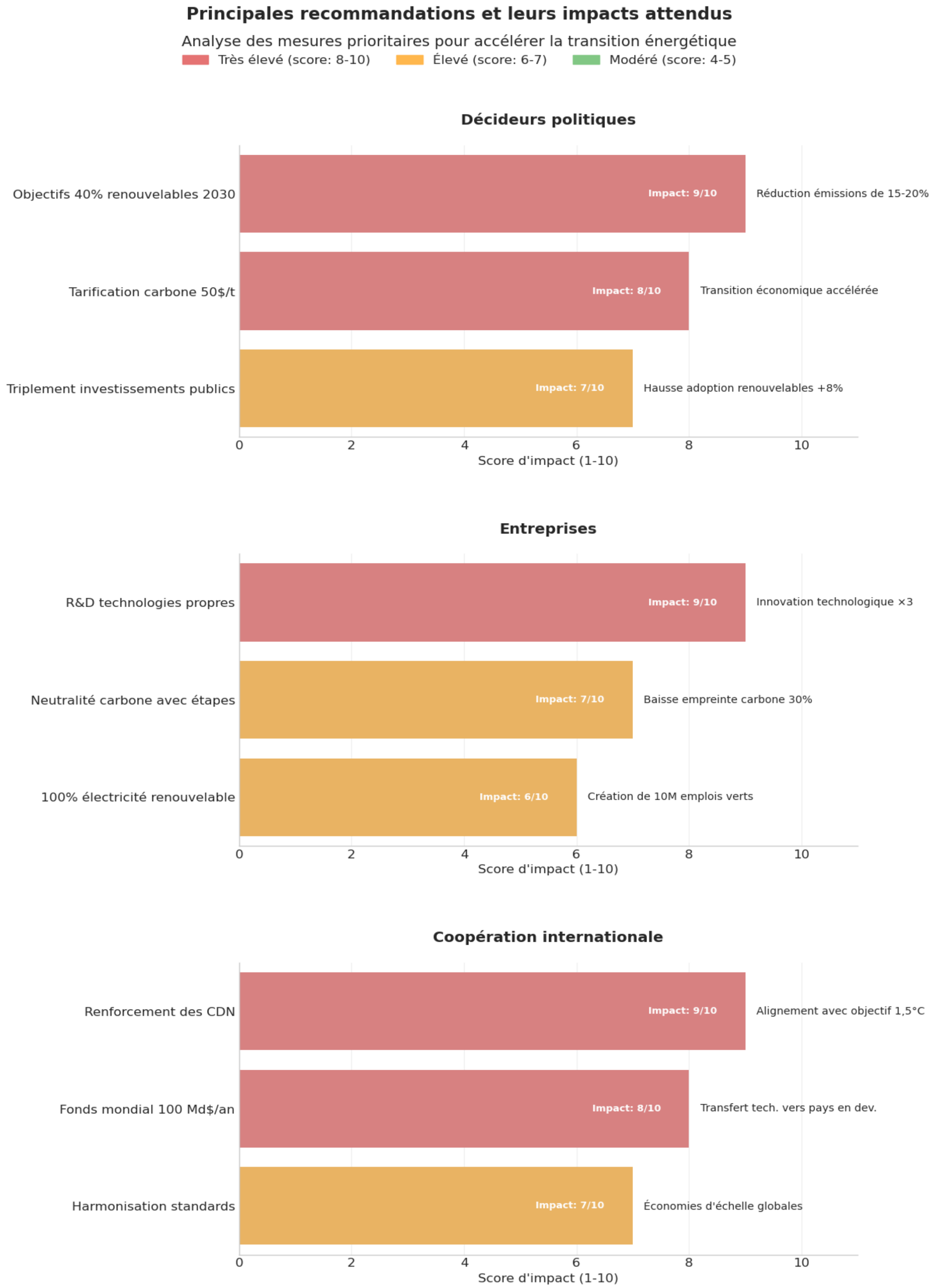
  # Add the Text "Impact: X/10" to the Right of Each Bar

  for j, row in enumerate(df_subset.itertuples()):

    axes[i].text(row.Score - 0.5, j, f"Impact: {row.Score}/10",

          va='center', ha='right', fontsize=9,

```
                    color='white', fontweight='bold')

# Common Legend
fig.subplots_adjust(top=0.9)  # Faire de la place pour la légende
legend_ax = fig.add_axes([0.1, 0.92, 0.8, 0.02])  # Axe spécial pour la légende
legend_ax.axis('off')  # Cacher l'axe

handles = [plt.Rectangle((0,0),1,1, color=colors[cat]) for cat in colors]
labels = [f"{cat} (score: {range})" for cat, range in
         zip(colors.keys(), ['8-10', '6-7', '4-5'])]
legend_ax.legend(handles, labels, loc='center', ncol=3, fontsize=12)

# Global Title with More Spacing
plt.figtext(0.5, 0.96, 'Principales recommandations et leurs impacts attendus',
        ha='center', fontsize=16, fontweight='bold')

# Separate Subtitle to Avoid Overlaps
plt.figtext(0.5, 0.94, 'Analyse des mesures prioritaires pour accélérer la transition énergétique',
        ha='center', fontsize=14)
plt.tight_layout(rect=[0, 0, 1, 0.9])
plt.subplots_adjust(hspace=0.4)
plt.savefig('recommandations_impacts.png', dpi=300, bbox_inches='tight')
plt.show()
```



Principales recommandations et leurs impacts attendus
Analyse des mesures prioritaires pour accélérer la transition énergétique
Très élevé (score: 8-10)
Élevé (score: 6-7)
Modéré (score: 4-5)
Décideurs politiques
Objectifs 40% renouvelables 2030
Impact: 9/10
Réduction émissions de 15-20%
Tarification carbone 50$/t
Impact: 8/10
Transition économique accélérée
Triplement investissements publics
Impact: 7/10
Hausse adoption renouvelables +8%
0
2
4
6
8
10
Score d'impact (1-10)
Entreprises
R&D technologies propres
Impact: 9/10
Innovation technologique ×3
Neutralité carbone avec étapes
Impact: 7/10
Baisse empreinte carbone 30%
100% électricité renouvelable
Impact: 6/10
Création de 10M emplois verts
0
2
4
6
8
10
Score d'impact (1-10)
Coopération internationale
Renforcement des CDN
Impact: 9/10
Alignement avec objectif 1,5°C
Fonds mondial 100 Md$/an
Impact: 8/10
Transfert tech. vers pays en dev.
Harmonisation standards
Impact: 7/10
Économies d'échelle globales
0
2
4
6
8
10
Score d'impact (1-10)

20.4.3. Analysis and Recommendations for Policymakers

20.4.3.1. Establishing Binding Energy Transition Targets (Impact: 9/10)

Establishing binding energy transition targets is a fundamental first step in accelerating the global energy transition. It is essential to set national and regional targets of at least 40% renewable energy by 2030, representing an average increase of 15 percentage points from current levels (25%). This measure would enable a significant reduction in emissions of 15-20% globally.

The effectiveness of these targets relies on transforming these objectives into binding national legislation, ensuring their permanence beyond electoral cycles and sending a clear signal to investors about the long-term direction of energy policies. These objectives must be accompanied by transparent monitoring and evaluation mechanisms, allowing regular adjustment of strategies based on progress and implementing sanctions for non-compliance.

This level of ambition would require the installation of approximately 3000 GW of additional renewable capacity by 2030, representing one of the most powerful policy levers available to governments committed to addressing climate change.

20.4.3.2. Implementing Carbon Pricing Policies (Impact: 8/10)

Implementing carbon pricing policies represents a powerful economic lever to accelerate the transition. Establishing a progressive carbon tax starting at $50/ton and increasing annually would internalize the environmental costs of emissions and stimulate innovation across all sectors of the economy.

This approach would generate approximately $250-300 billion in annual revenue globally, which is crucial to reinvest in the energy transition (70%) and support for vulnerable populations (30%) to ensure a just and socially acceptable transition. Developing effective emission trading systems would complement carbon taxation by creating a dynamic market for emission reduction.

Carbon pricing would make many currently less competitive clean technologies economically viable without requiring direct subsidies, effectively leveling the playing field between renewable and fossil energy sources. By putting a price on externalities, this mechanism would drive systemic change throughout the economy and stimulate innovation by creating market incentives for low-carbon solutions.

20.4.3.3. Strengthening Financial Support for the Transition (Impact: 7/10)

Financial support for the transition must be considerably strengthened to achieve climate goals. Public investments in renewable energy must be tripled by 2027, increasing from $300 to $900 billion annually on a global scale. This increase would boost renewable adoption by an additional 8% globally, creating a significant leverage effect on private investments with an estimated multiplier of 1:3.

Creating specific energy transition funds with adapted governance mechanisms would effectively target priority sectors, particularly for network infrastructure and emerging technologies. Facilitating access to financing for clean energy projects, particularly by reducing risk premiums and developing innovative financial instruments, is also essential to mobilize the $2,500 billion in annual investments needed globally.

This strengthened financial support would require innovative financing mechanisms and the strategic redirection of fossil fuel subsidies toward renewable energy development, effectively transforming the global energy investment landscape.

20.4.4. Analysis of Recommendations For Businesses:

20.4.4.1. Investing in R&D for Clean Technologies (Impact: 9/10)

Investment in technological innovation represents a differentiating factor for future competitiveness in a decarbonizing economy. Increasing R&D budgets for clean technologies, ideally up to 5% of revenue in energy-intensive sectors, could triple the pace of technological innovation in the energy sector, accelerating the development of breakthrough solutions that create sustainable competitive advantages.

This strategic allocation of resources would enable technological breakthroughs in critical areas such as energy storage, green hydrogen, and energy efficiency—technologies that will define market leadership in the coming decades. Participation in research consortia, particularly on energy storage where investment needs are estimated at $175 billion by 2030, allows for the pooling of costs and risks while accelerating development timelines.

Necessary global investments in clean energy R&D are estimated at $175 billion per year by 2030, representing a significant but strategic expenditure that can transform business models and position forward-thinking companies at the forefront of the low-carbon economy.

20.4.4.2. Adopting Carbon Neutrality Strategies with Clear Milestones (Impact: 7/10)

Integrating robust decarbonization strategies into business models is becoming imperative for companies in all sectors. Setting carbon neutrality targets with clear intermediate steps, typically a 45% reduction in emissions by 2030 compared to 2010, provides a structured approach that would reduce companies' carbon footprint by approximately 30% in the near term.

This approach would involve integrating an internal carbon price of $40-60/ton in investment decisions, helping to anticipate future regulations and significantly reduce transition risks. More than 350 large global companies have already committed to this path, demonstrating its feasibility and establishing new industry standards.

Investments in energy efficiency and on-site renewable energy that form part of these strategies can generate returns on investment of 15-20% while reducing carbon footprint, creating a compelling business case that aligns financial and environmental performance. Developing low-carbon intensity products and services also represents a strategic opportunity, with the global market for low-carbon solutions estimated at $4,500 billion by 2030.

20.4.4.3. Committing to 100% Renewable Electricity (Impact: 6/10)

Adopting responsible procurement practices is progressively transforming value chains across industries. The commitment to use 100% renewable electricity by 2030, already made by more than 350 large global companies, sends a strong signal to markets and would contribute to the creation of 10 million green jobs in the energy sector globally.

This approach would transform supply chains that represent on average 5.5 times a company's direct emissions, enabling comprehensive emissions reductions beyond organizational boundaries. By stimulating demand for large-scale renewable energy projects, these commitments accelerate market development and improve economics for the entire sector.

Beyond environmental benefits, 100% renewable electricity procurement could generate savings of 15-20% on long-term energy costs as renewable prices continue to fall below conventional alternatives. This approach creates a virtuous circle where environmental responsibility aligns with financial performance, helping to mainstream sustainable practices throughout the business community.

20.4.5. Analysis of Recommendations For International Cooperation:

20.4.5.1. Strengthening Nationally Determined Contributions (NDCs) (Impact: 9/10)

Coordinating climate policies amplifies the impact of national efforts and is essential for effective global action. Strengthening the ambition of Nationally Determined Contributions (NDCs) is necessary to bridge the current gap of 25-28 Gt CO_2 between commitments and the trajectory compatible with 1.5°C, aligning national commitments with this critical climate limitation objective.

This process would require upward revision of ambitions during the next Paris Agreement cycles, supported by enhanced transparency mechanisms and increased accountability among signatory nations. These elements are key for restoring confidence in international climate cooperation and ensuring the credibility of global climate governance.

By creating a coordinated framework for emissions reduction, strengthened NDCs would drive policy coherence across regions and establish a more predictable environment for investment in low-carbon solutions. This approach represents the backbone of international climate action, upon which other cooperative measures can build.

20.4.5.2. Creating a Global Fund for Clean Technology Access (Impact: 8/10)

Strengthening technology transfers is crucial to accelerate the diffusion of low-carbon solutions globally. Creating a global fund for access to clean technologies of $100 billion per year, as promised in international agreements, would support developing countries in their transition to renewable energy systems.

This fund would facilitate technology transfer to developing countries and enable the training of 500,000 renewable energy experts by 2030, building essential human capacity in regions where it's most needed. By reducing inequalities in access to clean technologies for the 759 million people currently without electricity, this approach addresses both climate and development objectives simultaneously.

The fund would accelerate the deployment of solutions adapted to local contexts and constitute a concrete implementation of the principle of common but differentiated responsibilities, a foundational concept in international climate cooperation. This financial mechanism would be complemented by dedicated platforms and exchange programs that facilitate knowledge and expertise sharing, accelerating the adoption of best practices across diverse geographic and economic contexts.

20.4.5.3. Harmonizing International Standards and Regulations (Impact: 7/10)

Harmonizing standards and regulations reduces trade barriers and accelerates the deployment of clean technologies on a global scale. Developing international standards for renewable energy technologies facilitates interoperability and generates significant economies of scale, making clean energy more affordable worldwide.

This harmonization would facilitate cross-border exchanges of clean electricity, creating a potential market of $150 billion by 2030, and would reduce trade barriers for low-carbon technologies. The development of common certifications for green electricity would strengthen consumer confidence and establish clear benchmarks for environmental performance.

Creating an equitable carbon border adjustment mechanism, respecting WTO principles and differentiated capabilities of countries, would avoid carbon leakage while preserving industrial competitiveness. Furthermore, implementing international sectoral initiatives targeting hard-to-decarbonize industries (steel, cement, transport), which represent 30% of global emissions, allows collective solving of specific technological challenges that no single country can address effectively alone.

20.5. In-depth Analysis of Implications:

1. **Prioritization**: The very high impact measures (scores 8-10) primarily concern setting ambitious targets, carbon pricing, and financing innovation - suggesting these levers should be activated as a priority.
2. **Complementary approaches**: The balanced distribution of recommendations between policymakers, businesses, and international cooperation highlights the need for coordinated actions at all levels.
3. **Cost-effectiveness**: The highest-rated measures are not necessarily the most expensive, but those that create a systemic effect (like carbon pricing) or establish a clear framework for economic actors.
4. **Temporal dimension**: The recommendations combine immediate-effect actions (like 100% renewable electricity) and longer-term structural transformations (R&D, standards harmonization).
5. **Implementation barriers**: Despite their high potential impact, these recommendations face significant obstacles: political resistance, financial constraints, and the complexity of international coordination.

20.6. Future Perspectives

20.6.1. Anticipated Technological Developments

Advances in energy storage will profoundly transform electrical systems. The expected reduction in battery costs of 60% by 2027, dropping from $137/kWh currently to about $55/kWh, will make storage competitive in most applications. The development of long-duration storage technologies, such as green hydrogen or compressed air, will address seasonal flexibility needs, with a projected global capacity of 100 GWh by 2030. The massive integration of distributed storage, with more than 5 million residential systems planned by 2027, will create new opportunities for smart grids and consumer participation.

New generation renewable energies will significantly improve technical and economic performance. Solar panels with efficiency exceeding 25%, compared to 20-22% currently, will increase energy production by 20% for the same surface area. Floating offshore wind turbines for deep waters, with a global technical potential of 7,000 GW, will open new territories for wind exploitation. Advanced biofuels without competition with food, using agricultural and forest residues or dedicated crops on marginal lands, will reach a production of 30-35 billion liters by 2030, reducing transport sector emissions by 70% compared to fossil fuels.

The deployment of smart grids will constitute the backbone of decentralized and flexible energy systems. Installing smart meters in 70% of households in developed countries by 2027, representing more than 850 million units, will enable dynamic demand management. Predictive algorithms to balance supply and demand, using artificial intelligence and big meteorological data, will reduce reserve capacity needs by 30%. Increased flexibility through digitalization will allow the integration of up to 80% variable energies in some networks, compared to 25-30% currently, while maintaining system stability and resilience.

20.6.2. Societal Transformations

The democratization of energy redistributes power in the energy system. The multiplication of local energy communities, with an estimated potential of 500,000 initiatives by 2030 in the European Union, transforms consumers into active "prosumers." The development of collective self-consumption, allowing multiple users to share a renewable installation, could concern 25% of households in developed countries by 2035. Increased citizen participation in energy decisions, through mechanisms like participatory budgets or citizens' conventions, strengthens social acceptability of infrastructure and accelerates local transitions.

Behavior evolution constitutes a complementary lever to technological advances. Growing awareness of individual carbon footprints, with 68% of global consumers declaring themselves ready to modify their habits, creates demand for low-carbon products and services. Adopting less energy-intensive lifestyles, such as soft mobility or digital sobriety, could reduce individual footprints by 20-25% in developed countries. The emergence of new forms of shared electric mobility, with a projection of 30 million car-sharing vehicles by 2030, is transforming the transport industry and reducing the need for individual vehicles.

Economic transformations induced by the energy transition are reshaping labor markets and value chains. The anticipated creation of 30 million jobs in renewable energies by 2030, compared to 12 million currently, largely compensates for the estimated losses of 5 million in fossil sectors. The progressive decline of traditional fossil industries, with a 40% reduction in thermal coal production by 2040, necessitates regional diversification strategies and professional reconversion. The emergence of new circular economic models, integrating the recovery and recycling of materials from end-of-life renewable technologies, creates economic opportunities while reducing the environmental impact of the transition.

20.6.3. Persistent Challenges

The issue of critical materials represents a strategic challenge for the large-scale deployment of clean technologies. Supply tensions for rare earth elements and strategic metals, with demand increases of 450% for lithium and 400% for cobalt by 2050, necessitate diversified supply strategies. The development of recycling and alternatives, such as cobalt-free batteries or permanent magnets using fewer rare earths, reduces pressure on primary resources. Geopolitical issues related to resources, with 70% of global rare earth production concentrated in China, call for strengthened international cooperation and strategic partnerships.

Climate justice constitutes an essential dimension of a sustainable energy transition. Inequalities in access to clean technologies, with 759 million people without access to electricity, necessitate mechanisms of international solidarity and technology transfer. The equitable distribution of transition costs, through progressive fiscal policies and compensation mechanisms, is essential for its social acceptability. The protection of communities most vulnerable to climate change impacts, who contribute least to emissions, must be integrated into adaptation and mitigation strategies for a truly just transition.

Managing intermittency of renewable energies represents a major technical challenge. The massive flexibility needs in electrical systems, estimated at 310 GW of new flexible capacities by 2030 in the European Union, require considerable investments in storage and networks. Regional and international coordination of networks, through strengthened interconnections and harmonized market mechanisms, optimizes the use of complementary renewable resources. The development of weather forecasting capabilities, with systems able to predict solar and wind production with 95% accuracy up to 48 hours in advance, reduces uncertainties and system balancing costs.

This comprehensive analysis demonstrates that despite significant progress in the deployment of renewable energies, we are still far from an energy transition rapid enough to achieve global climate objectives. The next five years will be decisive for accelerating this transition and putting the world on a trajectory compatible with limiting warming to 1.5°C. This will require unprecedented efforts across all sectors and regions of the world, as well as strengthened international cooperation despite current geopolitical tensions.

Références

Agence Internationale de l'Énergie (AIE). (2023). *World Energy Outlook 2023*. IEA Publications.

BP. (2023). *Statistical Review of World Energy 2023*, 72ème édition.

Ember. (2023). *Global Electricity Review 2023*. https://ember-climate.org/insights/research/global-electricity-review-2023/

GIEC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IRENA. (2023). *Renewable Capacity Statistics 2023*. International Renewable Energy Agency.

IRENA. (2022). *Global Energy Transition Outlook 2022: 1.5°C Pathway*. International Renewable Energy Agency.

Lazard. (2022). *Lazard's Levelized Cost of Energy Analysis — Version 16.0*. https://www.lazard.com/perspective/levelized-cost-of-energy-2022/

Our World in Data. (2023). *Energy mix and consumption by country and region*. https://ourworldindata.org/energy-mix

REN21. (2023). *Renewables 2023 Global Status Report*. Paris: REN21 Secretariat.

Ritchie, H., Roser, M., & Rosado, P. (2023). *CO_2 and Greenhouse Gas Emissions*. Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Banque Mondiale. (2023). *World Development Indicators: Energy and Mining*. Banque Mondiale. https://datatopics.worldbank.org/world-development-indicators/

Système de données sur les gaz à effet de serre (EDGAR). (2023). *Emissions Database for Global Atmospheric Research, version 8.0*. Commission européenne, Centre commun de recherche (JRC).

Global Carbon Project. (2023). *Global Carbon Budget 2023*. Earth System Science Data.

IEA & IRENA. (2023). *Renewable Power Generation Costs in 2022*. International Renewable Energy Agency & International Energy Agency.