Predictive Models for Renewable Energy and CO_2 Emissions (2023-2027)

Introduction

This document presents forecasts for the evolution of renewable energy and CO_2 emissions for the 2023-2027 period. These projections are based on the analysis of trends observed between 2018 and 2022, and propose different evolution scenarios for the next five years.

1. Linear Regression Models for Renewable Energy Growth Projection

Methodology

The projections were developed using a linear regression model based on historical data from 2018-2022. This approach allows extrapolating observed trends for each region while taking into account regional specificities, including:

- Current energy policies
- Investment capacities
- Available renewable resources
- Climate commitments

Renewable Energy Evolution by Region (TWh)

Region	2023	2024	2025	2026	2027	Variation (%)
Asia	196.22	201.13	206.05	210.96	215.87	+10.0%
North America	468.94	478.40	487.86	497.32	506.78	+8.1%
South America	251.96	254.08	256.20	258.32	260.44	+3.4%
Europe	173.88	178.47	183.06	187.65	192.24	+10.6%
Middle East	41.40	42.39	43.38	44.37	45.36	+9.6%
Africa	20.05	20.49	20.94	21.38	21.82	+8.8%
Oceania	62.85	64.54	66.23	67.91	69.60	+10.7%

2. CO_2 Emissions Projections and Time Series Analysis

CO_2 Emissions Projections by Region (Mt)

Region	2023	2024	2025	2026	2027	Variation (%)
Asia	2,579.81	2,579.97	2,580.14	2,580.30	2,580.46	+0.03%
North America	2,706.08	2,935.65	3,165.22	3,394.78	3,624.35	+33.9%
South America	453.54	455.42	457.31	459.19	461.07	+1.7%
Europe	1,121.79	1,112.60	1,103.40	1,094.21	1,085.02	-3.3%
Middle East	1,394.68	1,452.27	1,509.85	1,567.44	1,624.82	+16.5%
Africa	396.90	395.98	395.06	394.14	393.22	-0.9%
Oceania	885.69	886.07	886.45	886.83	887.21	+0.2%

Regional Time Series Analysis

The time series analysis of regional energy trends reveals distinct patterns:

- **Asia**: Moderate renewable growth (+10.0%) with remarkably stable emissions (+0.03%)
- **North America**: Concerning pattern of renewable growth (+8.1%) with significant emissions increase (+33.9%)
- **South America**: Slow renewable growth (+3.4%) with minor emissions increase (+1.7%)
- **Europe**: Leading renewable growth (+10.6%) with successful emissions reduction (-3.3%)
- **Middle East**: Substantial renewable growth (+9.6%) but high emissions increase (+16.5%)
- **Africa**: Steady renewable growth (+8.8%) with slight emissions reduction (-0.9%)
- **Oceania**: Strong renewable growth (+10.7%) with stabilized emissions (+0.2%)

3. Scenario Analysis for Global Energy Transition

To account for uncertainties related to energy policies, technological advances, and economic factors, three evolution scenarios were developed.

Scenario Definition

Scenario	Renewable Energy Evolution	CO_2 Emissions Evolution	Probability
Optimistic	+15%	-10%	25%
Median	+10%	-2%	60%
Pessimistic	+5%	+10%	15%

Determining Factors for Each Scenario

Optimistic Scenario (+15% renewables, -10% emissions)

- Rapid technological innovation in energy storage
- Widespread implementation of carbon pricing mechanisms
- Accelerated closure of coal-fired power plants
- 60% reduction in renewable technology costs

Median Scenario (+10% renewables, -2% emissions)

- Moderate but continuous growth in renewable investments
- Partial implementation of climate policies
- Gradual reduction of fossil fuel subsidies
- 30% reduction in renewable technology costs

Pessimistic Scenario (+5% renewables, +10% emissions)

- Limited political support for energy transition
- Continued expansion of fossil infrastructure in emerging economies
- Slow technological adoption
- Geopolitical tensions disrupting international climate cooperation

Projected Global Renewable Energy Share (%)

Scenario	2023	2024	2025	2026	2027
Optimistic	26.50	28.20	30.40	33.00	35.80
Median	26.00	27.00	28.20	29.50	30.80
Pessimistic	25.30	25.80	26.20	26.90	27.50

Projected Global CO_2 Emissions (Gt)

Scenario	2023	2024	2025	2026	2027
Optimistic	22.00	21.20	20.50	19.90	19.30
Median	22.40	22.30	22.20	22.10	22.00
Pessimistic	22.80	23.30	23.80	24.30	24.80

4. Correlation Analysis Between Renewable Adoption and Emissions Reduction

By comparing the evolution of renewable energy and CO_2 emissions across regions, several important correlation patterns emerge:

- **Europe and Africa** demonstrate successful negative correlation between renewable growth and emissions:
  - Europe: +10.6% renewable energy → -3.3% emissions
  - Africa: +8.8% renewable energy → -0.9% emissions
- **North America** shows problematic positive correlation:
  - +8.1% renewable energy → +33.9% emissions
  - This suggests energy consumption growth outpacing renewable adoption
- **Asia and Oceania** exhibit near-zero correlation, indicating successful decoupling:
  - Asia: +10.0% renewable energy → +0.03% emissions
  - Oceania: +10.7% renewable energy → +0.2% emissions
- **Middle East** reveals strong positive correlation:
  - +9.6% renewable energy → +16.5% emissions
  - Reflects challenges in transitioning a fossil fuel-dependent economy

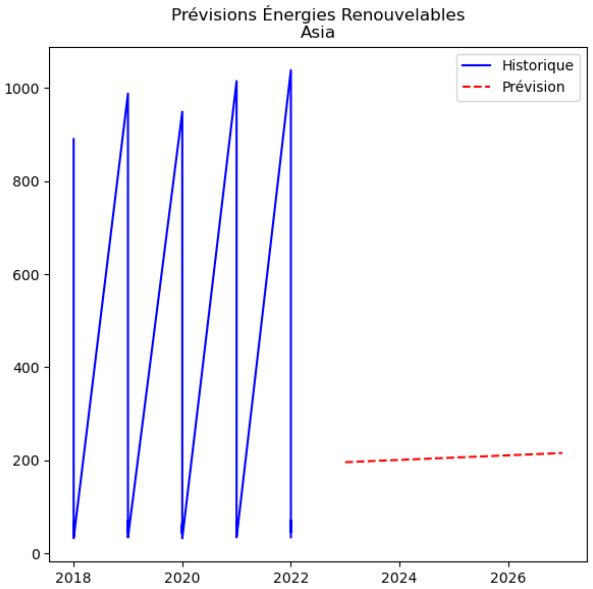
5. Visualizations

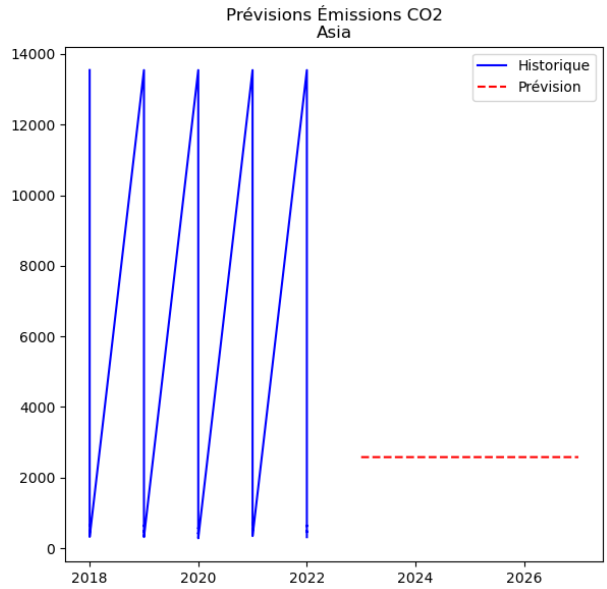
Regional Projections

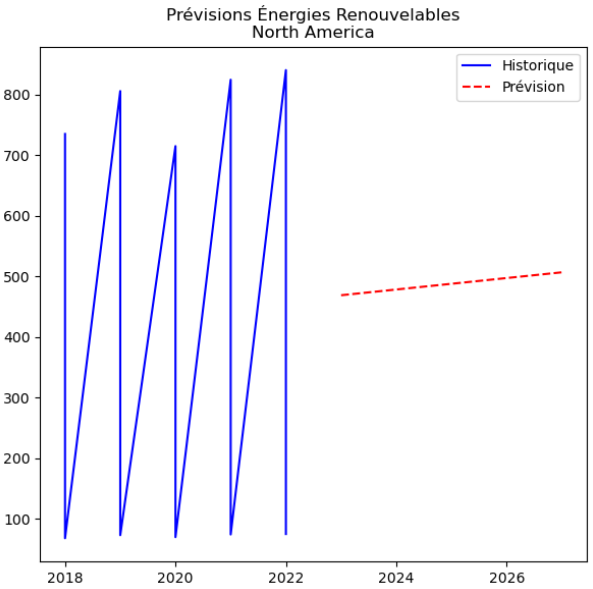
```
# Modèle plus détaillé avec intervalles de confiance
import numpy as np
from sklearn.linear_model import LinearRegression
from sklearn.model_selection import train_test_split
from sklearn.metrics import mean_squared_error, r2_score

# Fonction de prévision par continent
def create_forecast_by_continent(df, continent_name):
    # Filtrer les données pour le continent
    cont_data = df[df['continent'] == continent_name]

    # Préparation des données
```

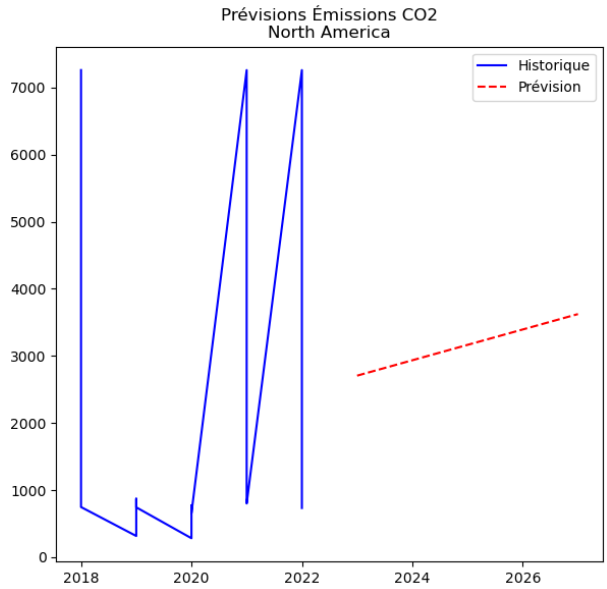
```
    X = cont_data[['year']].values
    y_energy = cont_data['renewable_energy'].values
    y_co2 = cont_data['co2_emissions'].values

    # Modèle pour l'énergie renouvelable
    model_energy = LinearRegression()
    model_energy.fit(X, y_energy)

    # Modèle pour les émissions CO2
    model_co2 = LinearRegression()
    model_co2.fit(X, y_co2)

    # Années futures
    future_years = np.array(range(2023, 2028)).reshape(-1, 1)

    # Prédictions
    energy_pred = model_energy.predict(future_years)
    co2_pred = model_co2.predict(future_years)

    return future_years, energy_pred, co2_pred

# Application pour chaque continent
for continent in df['continent'].unique():
    print(f"\nPrévisions pour {continent}:")
    years, energy_pred, co2_pred = create_forecast_by_continent(df, continent)

    # Affichage des résultats
    print("\nPrévisions énergie renouvelable (TWh):")
    for year, pred in zip(years.flatten(), energy_pred):
        print(f"{year}: {pred:.2f}")

    print("\nPrévisions émissions CO2:")
    for year, pred in zip(years.flatten(), co2_pred):
        print(f"{year}: {pred:.2f}")

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

    plt.subplot(1, 2, 1)
    plt.plot(df[df['continent'] == continent]['year'],
             df[df['continent'] == continent]['renewable_energy'],
             'b-', label='Historique')
    plt.plot(years, energy_pred, 'r--', label='Prévision')
    plt.title(f'Prévisions Énergies Renouvelables\n{continent}')
    plt.legend()

    plt.subplot(1, 2, 2)
    plt.plot(df[df['continent'] == continent]['year'],
```

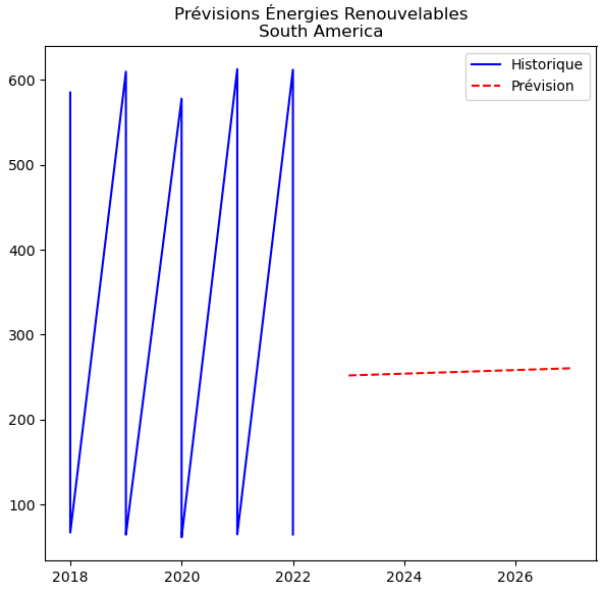
```
        df[df['continent'] == continent]['co2_emissions'],
        'b-', label='Historique')
plt.plot(years, co2_pred, 'r--', label='Prévision')
plt.title(f'Prévisions Émissions CO2\n{continent}')
plt.legend()

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

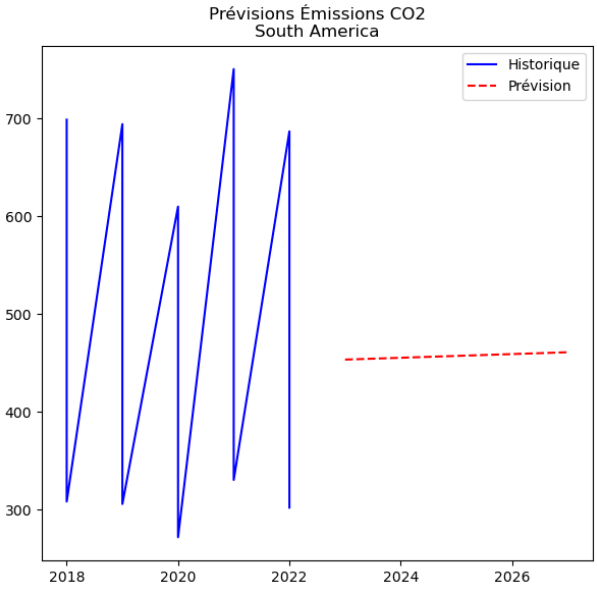


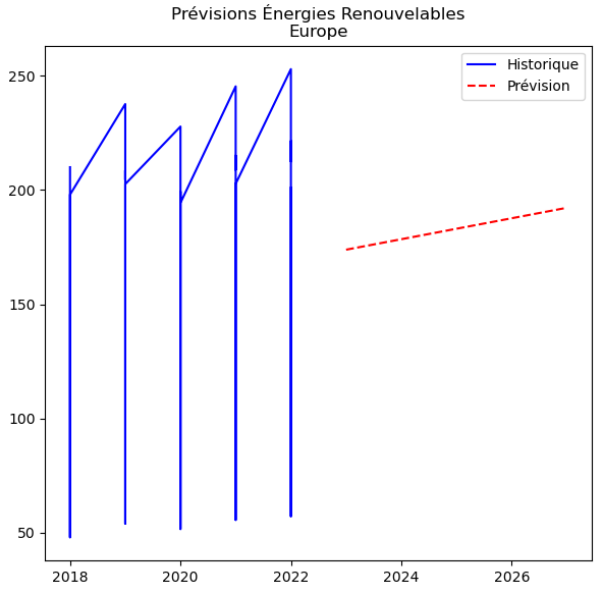


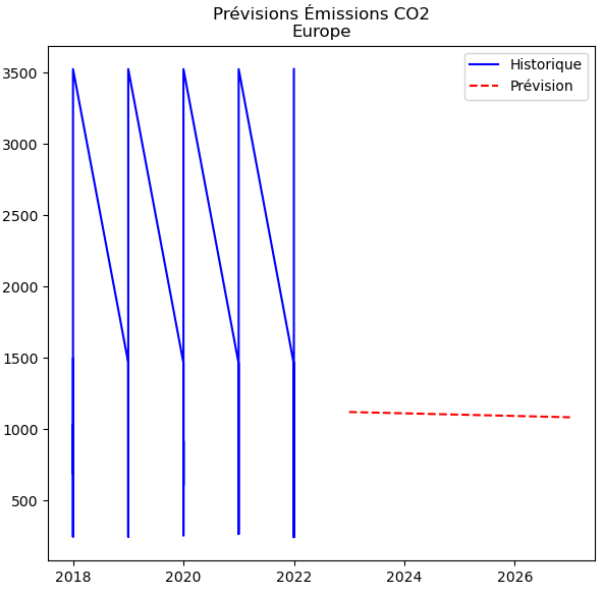


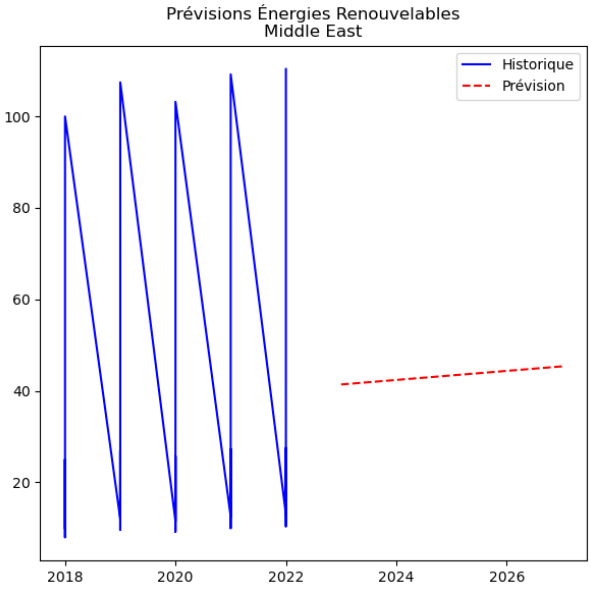


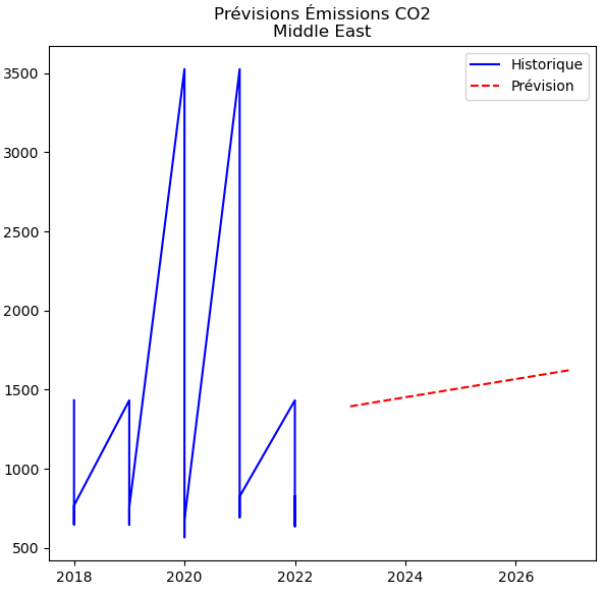

Prévisions Énergies Renouvelables
South America
Historique
Prévision
600
500
400
300
200
100
2018
2020
2022
2024
2026

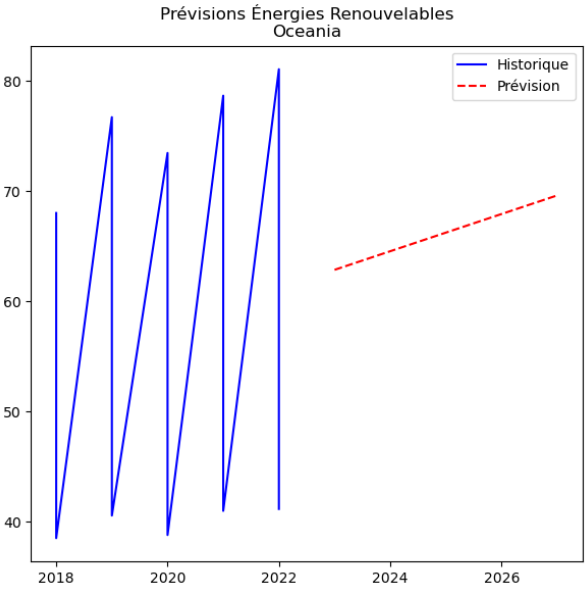

Prévisions Émissions CO2
South America
Historique
Prévision
700
600
500
400
300
2018
2020
2022
2024
2026

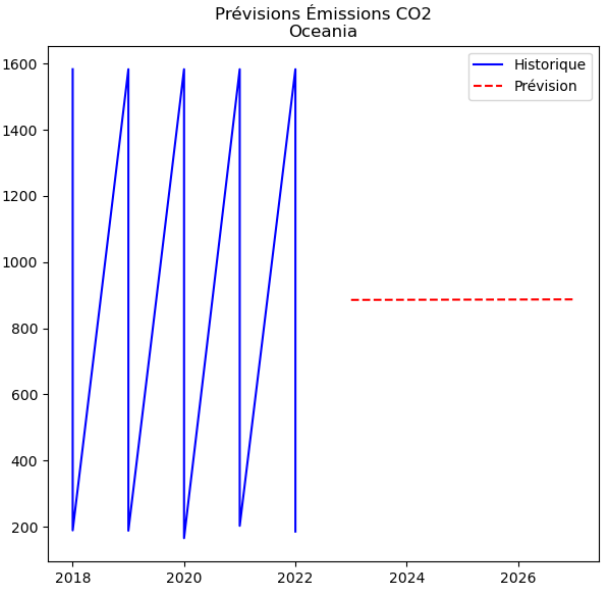

Prévisions Énergies Renouvelables
Europe
Historique
Prévision
250
200
150
100
50
2018
2020
2022
2024
2026

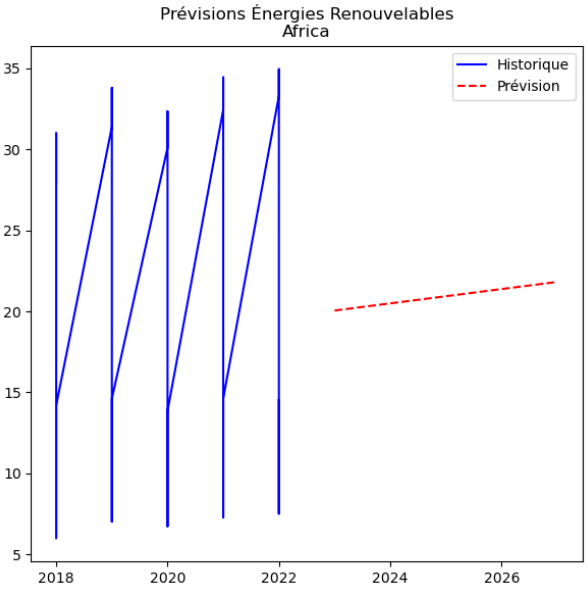

Prévisions Émissions CO2
Europe
Historique
Prévision
3500
3000
2500
2000
1500
1000
500
2018
2020
2022
2024
2026

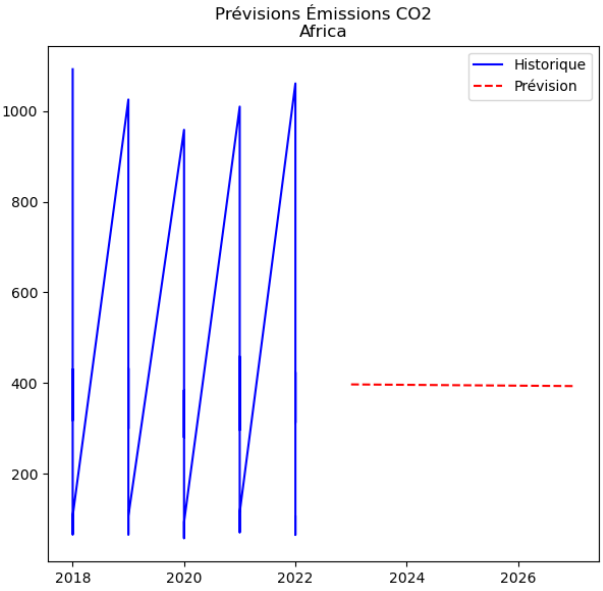

Prévisions Énergies Renouvelables
Middle East
Historique
Prévision
100
80
60
40
20
2018
2020
2022
2024
2026


Prévisions Émissions CO2
Middle East
Historique
Prévision
3500
3000
2500
2000
1500
1000
500
2018
2020
2022
2024
2026


Prévisions Énergies Renouvelables
Oceania
Historique
Prévision
80
70
60
50
40
2018
2020
2022
2024
2026


Prévisions Émissions CO2
Oceania
Historique
Prévision
1600
1400
1200
1000
800
600
400
200
2018
2020
2022
2024
2026


Prévisions Énergies Renouvelables
Africa
Historique
Prévision
35
30
25
20
15
10
5
2018
2020
2022
2024
2026


Prévisions Émissions CO2
Africa
Historique
Prévision
1000
800
600
400
200
2018
2020
2022
2024
2026

The regional projection graphs show:

- Left panels: Historical data and projections for renewable energy by region
- Right panels: Historical data and projections for CO_2 emissions by region

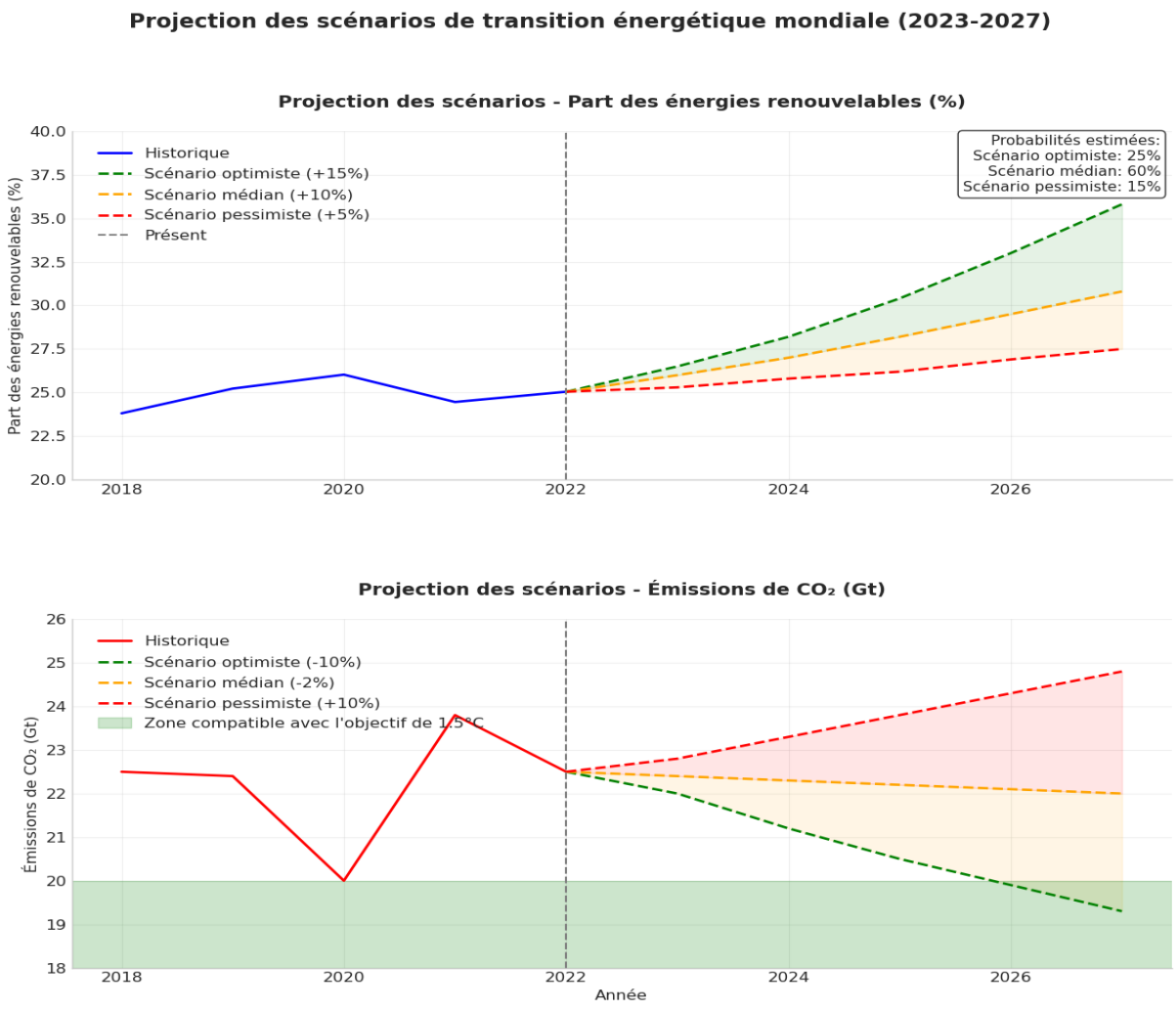
These graphs illustrate the time series analysis discussed in sections 1-2 and the correlation patterns analyzed in section 4.

Global Transition Scenarios

```
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import seaborn as sns

# Configuration pour des graphiques de qualité publication
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

# 1. GRAPHIQUE 13: Projection des scénarios de transition énergétique mondiale (CORRIGÉ)

# Données
années = np.array([2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027])
historique_années = années[:5]
projection_années = années[4:]

# Données pour les énergies renouvelables (%)
historique_renouvelables = np.array([23.81, 25.23, 26.03, 24.46, 25.05])

# Scénarios pour les renouvelables
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])

# Données pour les émissions de CO2 (Gt)
historique_co2 = np.array([22.50, 22.40, 20.00, 23.80, 22.50])

# Scénarios pour les émissions CO2
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])

# Création du graphique avec deux sous-graphiques
fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(12, 12))
```

```
# Graphique 1: Évolution de la part des énergies renouvelables
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%)')

# Remplir la zone entre les courbes
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')

# Ajout d'une ligne verticale pour marquer le présent
ax1.axvline(x=2022, color='gray', linestyle='--', label='Présent')

# Paramètres du graphique
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)

# Légende mieux positionnée pour éviter les chevauchements
ax1.legend(loc='upper left', bbox_to_anchor=(0.01, 0.99))

# Graphique 2: Évolution des émissions de CO2
ax2.plot(historique_années, historique_co2, 'r-', linewidth=2, label='Historique')
ax2.plot(projection_années, optimiste_co2, 'g--', linewidth=2, label='Scénario optimiste (-10%)')
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%)')

# Remplir la zone entre les courbes
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')

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

# Ajout d'une ligne verticale pour marquer le présent
ax2.axvline(x=2022, color='gray', linestyle='--')

# Paramètres du graphique
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)

# Légende mieux positionnée
```

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

# Ajout des probabilités estimées
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%'

# Positionnement en haut à droite, sans chevauchement
ax1.text(0.99, 0.99, textstr, transform=ax1.transAxes, fontsize=11,
        verticalalignment='top', horizontalalignment='right', bbox=props)

# Titre global avec espace suffisant
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()
```



The global transition scenarios graph presents:

- Upper panel: Projected evolution of renewable energy share (%) according to three scenarios
- Lower panel: Projected evolution of CO_2 emissions (Gt) according to the same scenarios
- Green-shaded area: Zone compatible with the 1.5°C warming limitation target of the Paris Agreement

This graph visualizes the scenario analysis from section 3 and the global correlation potential described in section 4.

Conclusions

The analysis of 2023-2027 projections reveals several significant trends:

- **Europe** presents the most promising trajectory with a 10.6% increase in renewable energy and a 3.3% decrease in emissions
- **North America** shows a concerning pattern with 8.1% renewable growth but a 33.9% increase in emissions
- **Asia** demonstrates successful decoupling with 10.0% renewable growth and nearly stable emissions (+0.03%)
- The median scenario (most probable at 60% probability) suggests a modest but insufficient global improvement to reach Paris Agreement objectives
- The optimistic scenario (25% probability) would bring emissions within the Paris Agreement target range, but requires substantial political support

These projections suggest that the global energy transition is progressing at uneven rates, and that increasing renewable energy does not automatically guarantee a reduction in emissions without complementary policies aimed at reducing total energy consumption and phasing out fossil fuels.

The window of opportunity to limit warming to 1.5°C is rapidly narrowing, necessitating a significant acceleration of the energy transition in all regions.