Global Energy and Carbon Efficiency: Comprehensive Analytical Framework

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GitHub: https://github.com/KarthikKuppala/GlobalEnergy_and_CarbonEfficiency

Tools: Python, SQL, Duck DB, Snowflake compatible

Research Question: To what extent does the generation, utilization, and carbon intensity of energy change among nations—and where do the most significant efficiency and risk indicators remain?

Abstract:
Worldwide energy systems are experiencing a swift evolution fueled by growing demand, economic expansion, and heightened pressure to lower greenhouse gas emissions. Grasping the differences in energy production, consumption, and carbon emissions among countries is crucial for recognizing inefficiencies and long-term climate hazards

This research investigates the differences in energy production, consumption, and carbon intensity among countries based on worldwide energy statistics from Our World in Data. Utilizing a structured framework of KPI, OKR, KRI, and RFM through Snowflake-compatible SQL and DuckDB, we measure long-term energy patterns, pinpoint efficiency shortfalls, and emphasize carbon risk differences.

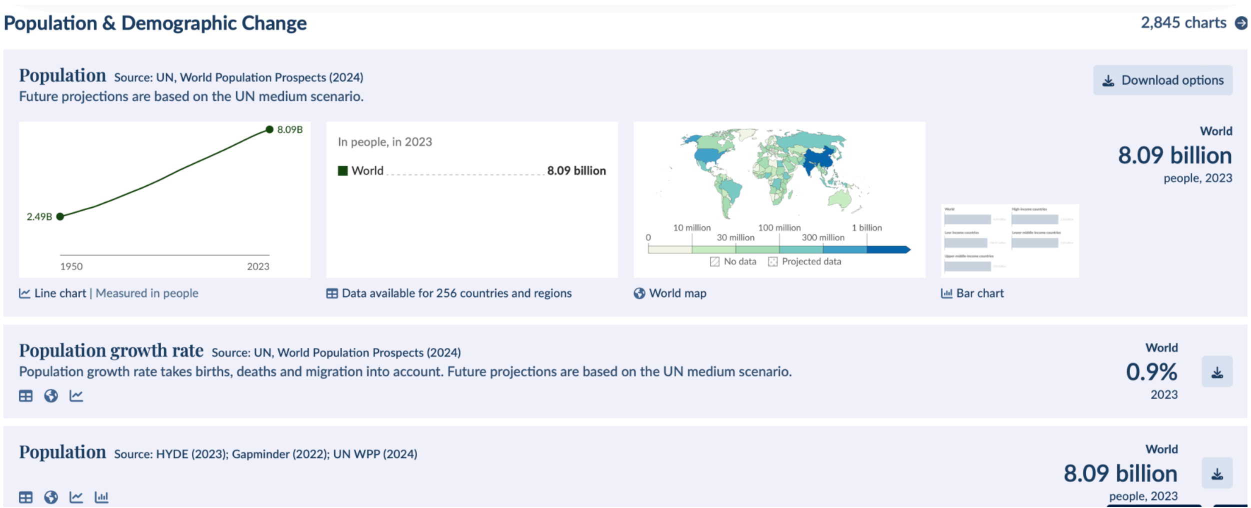
1. Introduction

In the last hundred years, worldwide energy use has continuously increased in tandem with population expansion and economic progress, with fossil fuels being the primary energy source. Although this growth has led to improved living standards, it has also caused significant greenhouse gas emissions, heightening worries regarding climate change, environmental harm, and future sustainability.

Over the past few decades, renewable energy technologies have grown swiftly, aided by decreasing expenses and policy encouragement. Nevertheless, the degree to which renewable energy sources have replaced fossil fuels, rather than simply meeting increasing energy demand, is still an unresolved empirical issue. Moreover, countries vary significantly in the efficiency with which they transform energy into economic productivity and in the carbon intensity of their electricity generation. These differences hinder global decarbonization initiatives and question uniform policy approaches.

This research aims to address the following question: To what extent does the generation, utilization, and carbon intensity of energy change among nations—and where do the most significant efficiency and risk indicators remain? To tackle this issue, the analysis employs a systematic, metrics-based framework typically utilized in assessing organizational performance. The study offers a systematic and interpretable perspective on global energy trends and risks by repurposing KPIs, OKRs, KRIs, and RFMs for macro-level energy data

2. Data Sources and Assumptions



(Figure 1: Our World in Energy Dashboard)

The analysis utilizes the Our World in Data global energy dataset, compiling historical energy, economic, and emissions information from various international sources. The dataset features observations at the country level spanning multiple decades, encompassing metrics like population, gross domestic product, primary energy use, electricity production, consumption of renewable and fossil fuels, greenhouse gas emissions, as well as indicators of energy efficiency and carbon intensity.

Raw data was imported from a CSV file and analyzed using Python and Pandas. The sanitized dataset was saved in a DuckDB database as one fact table, allowing efficient analytical queries through SQL. Only observations at the country level with valid ISO country codes were kept; collective entities like "World" or continental groups were removed to prevent double counting and maintain consistency in cross-national comparisons.

A number of assumptions direct the analysis. Initially, absent values in earlier years are viewed as authentic data scarcity instead of processing mistakes. Metrics like GDP, greenhouse gas emissions, and carbon intensity are examined solely for the years where the foundational data exist. No artificial imputation was conducted, as it might create misleading trends. Secondly, greenhouse gas emissions serve as a proxy for carbon production, acknowledging that this metric encompasses gases in addition to carbon dioxide, yet it continues to be a key indicator in worldwide energy assessments. Ultimately, all financial figures are considered to be adjusted for inflation according to the source dataset

3. Methodology and Metrics framework

The methodological framework integrates descriptive analytics, comparative analysis, and regression modeling into a cohesive performance-metrics system. Four types of metrics are specified. Key Performance Indicators reflect the overall scale and growth of the system, encompassing global primary energy use, electricity production, and total emissions. Objectives and Key Results signify guiding aims, like enhancing the use of renewable energy and boosting energy efficiency quantified as energy consumption per GDP unit. Key Risk Indicators emphasize the potential for environmental damage, especially regarding the carbon intensity of electricity production and emissions per capita. Ultimately, RFMs are modified to reflect long-term trends in energy usage habits, focusing on recency and consistency instead of transactional worth.

SQL queries run on the DuckDB database generate annual aggregates, national averages, and comparisons between developed and emerging economies. Nations are categorized into these groups according to their economic development status as outlined in the dataset information. Regression analysis is conducted to assess the correlation between energy intensity per GDP and the carbon intensity of electricity production. The model evaluates how much efficiency enhancements by themselves account for differences in carbon results.

Every analytical process is reproducible and suitable for cloud data warehouse settings, guaranteeing that outcomes can be re-run or expanded by using larger datasets or different time frames

4. Results and Analysis

4.1 Key Metrics

KPIs (Key Performance Indicator):

Metric	Observation
total_energy	Growing steadily from 35,465 TWh in 1965 to 44,111 TWh in 1969 — shows **overall global energy demand rising**.

total_fossil_consumption	Also rising, closely tracking total energy — indicates **fossil fuels still dominate** the energy mix in this period.
avg_energy_per_gdp	Slowly increasing — energy intensity per unit of GDP is rising slightly, meaning **economic growth is somewhat energy-intensive**.

Insight: The energy framework of the mid-to-late 1960s heavily depends on fossil fuels, with economic expansion linked to higher energy usage

KRIs (Key country-level risk indicators, 2022)

Metric	Observation
co2_per_capita	Small figures for certain countries, larger for others — underscores disparities in emissions among nations.
energy_per_gdp	Differs among nations — certain countries are more efficient in producing economic results.
carbon_intensity_elec	Wide variation: from 24 (Albania) to 633 (Algeria) — indicates electricity production relies on different fuel mixes, some clean, some carbon-heavy.

Insight: When making policy or investment choices, concentrate on countries with high carbon intensity for decarbonization initiatives

OKRs (Objectives and Key Results)

Metric	Observation
total_fossil_consumption	Demonstrates a consistent rise annually (1965–1969) — emphasizes a focus area for reduction objectives.
energy_per_gdp	Fairly consistent between 1.9 and 2.0 — may act as a standard KPI for enhancements in efficiency.

Insight: Although total energy may increase, you could establish OKRs to diminish the fossil fuel percentage compared to total energy.

RFMs (Renewables-Fossil Mix)

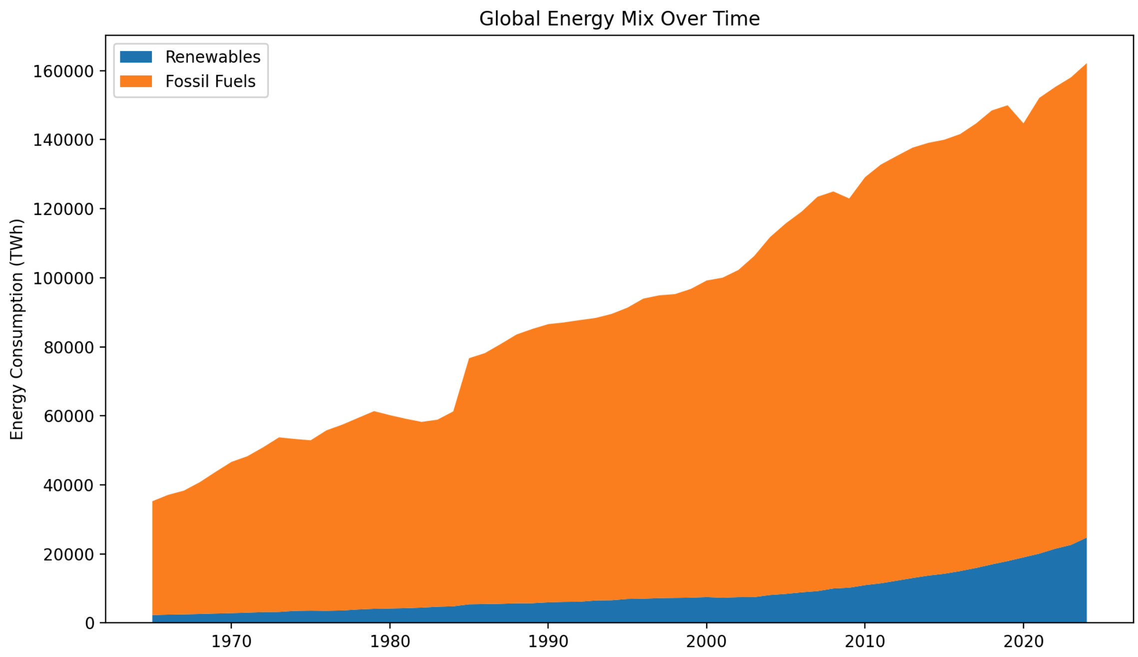
Metric	Observation
renewables	Slowly increasing from 2,302 TWh to 2,735 TWh — growth is modest relative to fossil fuels.
fossil_fuels	Rising rapidly — reinforces the need for transition policies.
total_energy	Mirrors KPIs, shows total demand growth.

Insight: Renewables are growing, but fossil fuels are still dominant. RFM data is perfect for tracking the energy transition over decades.

4.2 Worldwide Energy Expansion and Performance Metrics

Examination of essential performance metrics shows a distinct increase in worldwide primary energy use and electricity production over time. As the population and economic production grow, overall energy demand persists in rising, indicating that efficiency improvements haven't counterbalanced total growth. Greenhouse gas emissions show a comparable trend, suggesting that a complete decoupling of energy consumption and emissions has not been realized globally.

4.3 Energy Composition and Transition Dynamics



(Figure 2: Chart of Global Energy Mix and Energy Consumption)

RFM-style trend analysis indicates that although renewable energy usage rises consistently over time, fossil fuels continue to be the primary energy source during the observed timeframe. The expansion of renewable energy seems mainly additive instead of substitutive, enhancing current fossil fuel usage rather than replacing it. This trend indicates that structural inertia and increasing demand restrict the speed at which clean energy shifts lead to total emissions decreases.

4.4 Carbon Risk Metrics and International Differences

Key risk indicators reveal significant variations among countries. On average, developing economies demonstrate markedly greater carbon intensity in electricity generation than developed economies. Notably, energy efficiency quantified as energy per GDP unit shows little variation between the two groups. This suggests that greater carbon intensity in developing countries stems more from dependence on carbon-rich fuel mixtures and outdated infrastructure than from inefficiency.

4.5 Analysis of Regression

```
Regression Results
                            OLS Regression Results
==============================================================================
Dep. Variable:     carbon_intensity_elec   R-squared:                       0.073
Model:                               OLS   Adj. R-squared:                  0.067
Method:                    Least Squares   F-statistic:                     12.75
Date:                   Fri, 06 Feb 2026   Prob (F-statistic):           0.000467
Time:                           13:08:06   Log-Likelihood:                -1135.7
No. Observations:                    165   AIC:                             2275.
Df Residuals:                        163   BIC:                             2282.
Df Model:                              1
Covariance Type:               nonrobust
==================================================================================
                     coef    std err          t      P>|t|      [0.025      0.975]
----------------------------------------------------------------------------------
const            315.6831     32.901      9.595      0.000     250.716     380.650
energy_per_gdp    83.3169     23.330      3.571      0.000      37.249     129.385
==============================================================================
Omnibus:                        5.099   Durbin-Watson:                   2.163
Prob(Omnibus):                  0.078   Jarque-Bera (JB):                2.840
Skew:                          -0.038   Prob(JB):                        0.242
Kurtosis:                       2.362   Cond. No.                         3.48
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
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(Figure 3: Regression Results)

Regression findings show a positive and statistically significant connection between energy intensity per GDP and the carbon intensity of electricity. Nations that need greater energy to create economic output usually generate electricity with higher related emissions. The model accounts for only a small share of the variance in carbon intensity, indicating that elements like energy source mix, regulatory frameworks, and technology advancement significantly influence the outcome beyond mere efficiency

5. Discussion

The results highlight the constraints of concentrating only on energy efficiency as a means to achieve decarbonization. Although enhancing efficiency is essential and advantageous, it does not assure reduced carbon intensity, especially in areas where fossil fuels prevail in the energy composition. The continued reliance on fossil fuels in worldwide energy use underscores the difficulty of attaining significant emissions reductions without extensive structural transformation.

The gap between advanced and emerging economies brings significant fairness issues to light. Developing countries frequently encounter greater carbon intensity not from inefficiency but because of limited access to cleaner technologies and expensive infrastructure. Policy strategies that highlight emissions reductions while neglecting these structural limitations may unjustly impose greater burdens on nations with limited resources.

From a methodological standpoint, employing enterprise-style performance frameworks offers a consistent approach to understanding intricate, multi-faceted energy information. KPIs, OKRs, KRIs, and RFMs convert vague worldwide trends into understandable indicators of performance, advancement, and risk.

6. Limitations

This research depends on combined national data, which could obscure variations at sub-national levels and sector-specific trends. Moreover, greenhouse gas emissions are regarded as a unified total, restricting the capacity to differentiate between various sources of emissions. The regression analysis is deliberately straightforward and excludes other covariates like policy variables, fuel price fluctuations, or technology adoption rates. Future research could broaden the model to consider these elements.

7. Conclusion

This study shows that global energy systems continue to rely significantly on fossil fuels, even with the ongoing rise in renewables and better efficiency. Carbon intensity differs significantly among countries, with developing nations encountering greater risk mainly because of structural and infrastructural limitations instead of inefficiency alone. Enhancements in efficiency, though vital, are inadequate for achieving significant decarbonization unless accompanied by simultaneous modifications in energy production methods.

With the growing energy demand—especially due to the proliferation of data-heavy technologies like artificial intelligence—grasping these dynamics is becoming more critical. Upcoming studies ought to combine grid-level information, energy consumption by sector, and real-time workload data to enhance evaluation of the environmental effects of new technologies and guide fairer and more effective climate policies

8. References

https://ourworldindata.org/

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