# HPC on carbon emission trends based on grey forecasting and Topsis method

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**Abstract.** This study investigates the carbon footprint of high-performance computing (HPC) systems by developing integrated models to estimate energy consumption and associated carbon emissions. Using data from the 2023 World Energy Statistical Yearbook, we assess the global energy consumption of HPC systems under different utilization scenarios and predict future trends through grey forecasting. Our results show that HPC systems currently contribute to significant carbon emissions, with Asia being a major contributor. By incorporating the TOPSIS method with entropy weighting, we evaluate the environmental impact of transitioning to renewable energy sources and propose actionable recommendations to mitigate HPC's carbon footprint. This research highlights the urgent need for sustainable practices in HPC to align with global climate goals and provides valuable insights for policymakers and industry stakeholders.

**Keywords:** High-Performance Computing; Carbon Footprint; Grey Forecasting; TOPSIS Method; Environmental Impact.

## 1. Introduction

High-Performance Computing (HPC) mainly refers to the computational and fast and efficient computing, which is one of the fastest directions of information technology development to solve the requirements of applications for supercomputing performance through parallel computing[1]. High-performance computers are also commonly referred to as supercomputers. High-performance computing has become an important part of the discipline of computer science and technology. The branch refers to the research and development of high-performance computer technology from the aspects of architecture, parallel algorithms and software development, and high-performance computing, theoretical science and experimental science constitute the three pillars of scientific research. High-performance computing plays an indispensable role in national science and technology, national defense, industry, finance, services, and life. With the rapid development of the digital economy and the continuous expansion of the scale of HPC clusters, the problem of energy consumption has become a particularly serious problem, especially in terms of greenhouse gas emissions and resource use efficiency [2]. Promoting the deep integration of digital technology and the development of the energy industry, and building a clean, low-carbon, safe and efficient energy system have become the focus of current attention.

According to the International Energy Agency (IEA), the electricity consumption of data centers accommodating supercomputing accounts for 1.5%~2% of the world's total electricity consumption, which is roughly equivalent to the electricity consumption of the entire United Kingdom, and this proportion is expected to rise to 4% by 2030[3]. Based on the projections, the energy consumption of high-performance computing (HPC) systems is estimated to be between 448.872 TWh and 598.496 TWh[4]. This shows that the energy consumption of supercomputing systems running large models is extremely high, and HPC, including supercomputers, is becoming a major energy consumer, and the resulting environmental problems such as carbon emissions cannot be ignored. HPC-related equipment will generate a large amount of heat energy during operation, which will lead to an increase in the temperature of the machine, and excessive temperature will lead to data center downtime or even collapse, so in order to ensure the normal operation of HPC-related equipment, the equipment must be physically cooled by an external connection cooling system, which will also lead to a large amount of carbon emissions in the process. Therefore, it is very important to effectively reduce the carbon emissions generated by HPC operations, which is also an inevitable requirement to combat climate change and promote green development.

In this study, we analyzed the energy consumption and carbon emissions of high-performance computing (HPC) systems, and constructed a model to estimate the total carbon emissions generated by HPC energy use by incorporating multiple energy sources and their respective carbon emission factors. We used grey forecasting techniques to project HPC energy consumption and its associated carbon emissions from the future to 2030 [5]. In addition, the study explores the potential benefits of transitioning to renewable energy and makes actionable recommendations to mitigate the environmental impact of HPC operations [6]. By exploring the key importance of adopting sustainable practices in the field of HPC, it provides a theoretical basis for the green and clean operation of HPC.

## 2. Restatement of the Problem

Based on the methodological framework established in this study, we propose a systematic approach to evaluate and mitigate the environmental impacts of high-performance computing (HPC) energy consumption through five interconnected research objectives. First, we aim to develop a dual-scenario computational model to quantify annual HPC energy demand, contrasting theoretical maximum consumption under continuous full-capacity operation with real-world estimates based on typical utilization patterns, thereby establishing baseline parameters for environmental impact assessments. Building on this foundation, a comprehensive analytical framework will be constructed to calculate HPC-related carbon emissions, incorporating regionalized energy production profiles, temporal variations in national energy mixes, fuel-specific emission factors, and efficiency differentials across power generation modalities. To project future trajectories, a dynamic simulation system will integrate HPC growth forecasts with cross-sector energy demand trends, generating scenario-based emissions projections through 2030 while accounting for variables such as technological efficiency gains, energy source transitions, and policy-driven decarbonization initiatives.

Further analysis will focus on renewable energy transitions through parametric studies quantifying emission reduction potentials, including feasibility assessments of complete grid decarbonization scenarios, while enhancing modeling capabilities by incorporating secondary environmental metrics such as rare earth mineral demand for renewable infrastructure and water consumption for cooling systems—factors selected for their critical interdependence with energy transition strategies. Finally, the study will formulate a tiered intervention framework combining technological optimizations (e.g., liquid cooling advancements, workload scheduling algorithms) with policy mechanisms (carbon pricing, renewable energy credits), demonstrating model integration through machine learning-driven energy allocation systems that optimize computational efficiency and carbon intensity. These findings will inform formal policy recommendations urging the United Nations Advisory Board to explicitly incorporate HPC environmental impacts into the 2030 Sustainable Development Goals agenda, emphasizing the necessity of international coordination to mitigate the ecological footprint of compute-intensive technologies, as outlined in recent governance frameworks [4]. This integrated methodology bridges technical precision with policy relevance, offering a novel paradigm for managing the environmental externalities of advanced computing infrastructure.

## 3. Preparation of the Models

### 3.1 Assumptions

Assuming the energy mix (i.e., oil, renewable energy, etc.) remains constant over the years:Energymix changes are typically slow due to high infrastructure investment. This assumption allowsthe model to focus on energy consumption and emissions without frequent energy sourceshifts.

Assuming carbon emissions are directly proportional to energy consumption for electricity generation, with specific carbon emission factors for different energy sources:Differentenergy sources have established carbon emission factors. This proportionality simplifiescalculations and clarifies each energy source's role in total emissions.

Assuming most data centers use water cooling systems, requiring a quantifiable amount ofwater and producing a certain proportion of wastewater:Water cooling is common in HPCdata centers due to its efficiency, This assumption enables quantifying water use and wastew.ater impact.

### 3.2 Notations

These notations provide a clear framework for the mathematical models and calculations presented in subsequent sections.

The following notations are used throughout this paper to describe the models and calculations:

**Table 1.** notations

| **Symbol** | **Definition** |
|---|---|
| C | Total carbon emissions from HPC facilities (in $kgCO_2$) |
| E | Total energy consumption of HPC (in kWh) |
| $n_i$ | Proportion of energy source *i* in the grid |
| $F_i$ | Carbon emission factor of energy source *i* (in $kgCO_2/kWh$) |
| $T$ | Total arithmetic power of HPC (in EFLOPS) |
| $GCE$ | Arithmetic carbon efficiency of HPC (in $ktCO_2$/EFLOPS) |
| $W$ | Total arithmetic power of HPC (in EFLOPS) |
| $r_a$ | Arithmetic carbon efficiency of HPC (in $ktCO_2$/EFLOPS) |
| $F_w$ | Total arithmetic power of HPC (in EFLOPS) |
| $P_w$ | Arithmetic carbon efficiency of HPC (in $ktCO_2$/EFLOPS) |
| $T_W$ | Total pollutant emissions from wastewater (in kg) |

### 3.3 Model Development Overview

In this study, we constructed a model that can comprehensively evaluate HPC energy consumption and carbon emissions through multi-stage and multi-process, and ensure that the model is accurate and reliable. This model analyzes the historical global power consumption data to estimate the energy consumption of the HPC system in different operating scenarios, including full load and average utilization rate, and lays a solid foundation for the energy demand of the HPC system in different scenarios. Subsequently, a detailed model was developed to calculate total carbon emissions based on the energy mix and the specific carbon emission factors of each energy source, in which data from multiple energy sources such as coal, natural gas, and renewables were integrated, providing a comprehensive view of the carbon footprint associated with HPC operations. In this study, the grey prediction technique was used to predict future energy consumption and carbon emissions. In this study, the Ideal Solution Ranking Method (TOPSIS) based on the entropy weight method was used to evaluate the environmental impact and mitigation strategies of different energy sources, and finally the optimal strategies to identify and reduce the environmental impact were obtained. The model also incorporates the environmental impacts of water use and wastewater discharge, taking into account the correlation between water consumption and energy use in cooling systems, providing a more comprehensive assessment of the environmental footprint of HPC systems.

## 4. Results and Discussion

### 4.1 Global Energy Consumption of HPC Systems

According to the 2023 World Energy Statistics Yearbook, global electricity generation reached29,924.8 TWh, while data centers housing supercomputing accounted for 1.5% to 2% of thetotal global electricity consumption, i.e., it can be obtained that data centers housing super.computing used between 448.872 TWh and 598.496 TWh. 'T Current status and actual powerconsumption of the world's key developing arithmetic application areas in 2023 is shown in in figure1. Under full load conditions, this consumption range increases to 1,122.18 TWh to 1,496.24

TWh, as shown in figure2 and table1. This substantial energy demand underscores the critical need for energy efficiency improvements in HPC operations.

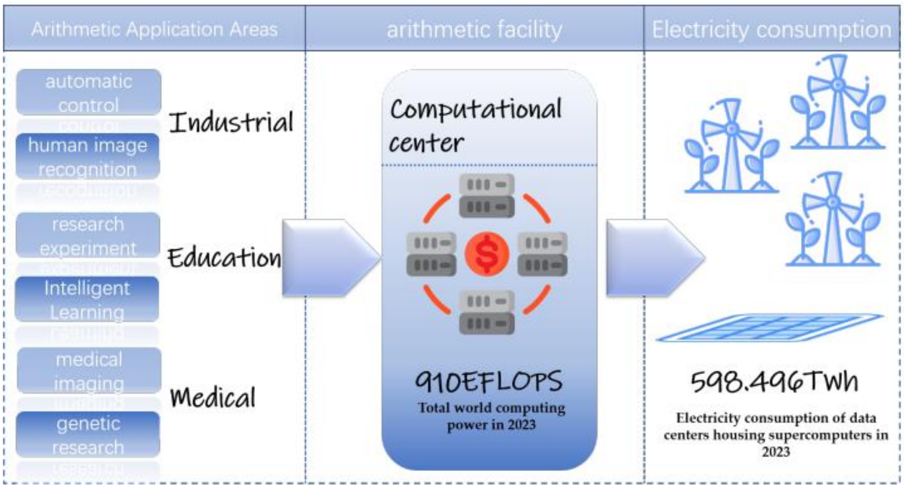

**Figure 1.** Current status and actual power consumption of the world's key developing arithmetic application areas

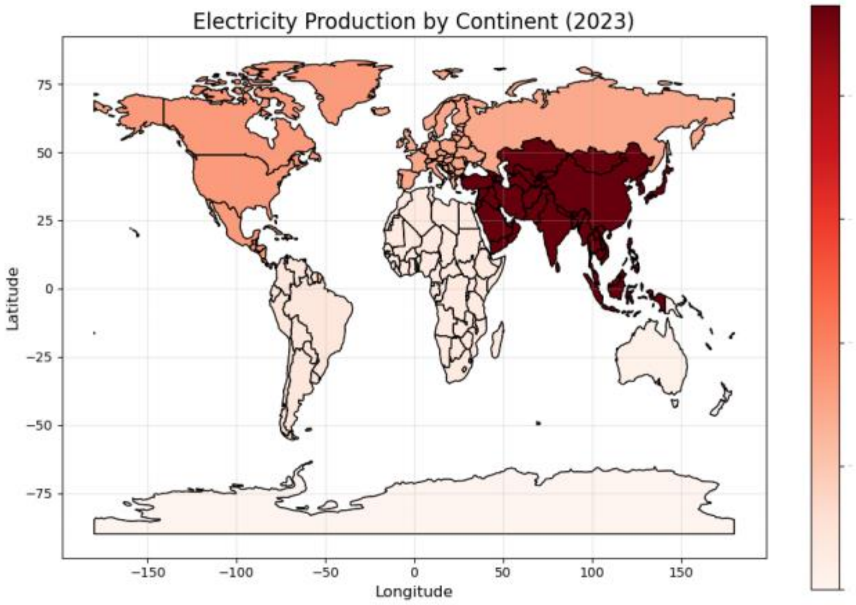

**Figure 2.** The amount of electricity produced in the seven continents in 2023

**Table 2.** Electricity consumption of data centre equipment at full load and average utilisation across seven continents in 2023

| Country | Africa | Asia | Europe | North America | South America | Oceania | Antarctica |
|---|---|---|---|---|---|---|---|
| Full Load(TWh) | 44.20 | 721.68 | 218.59 | 251.78 | 58.38 | 14.58 | 0 |
| Average Utilisation(TWh) | 17.68 | 288.67 | 87.44 | 100.71 | 23.35 | 5.83 | 0 |

### 4.2 Carbon Emissions from HPC Energy Consumption

Using our integrated model, we calculated the total carbon emissions resulting from HPC energy consumption. The results indicate that HPC systems currently contribute to approximately 212.99

million tons of CO2 emissions annually (Table 2 and figure 3). This figure highlights the significant environmental impact of HPC operations, particularly in regions with higher reliance on fossil fuels.

**Table 3.** The carbon emissions from different types of energy consumption

| Type of energy | Carbon Emissions (MT) |
|---|---|
| Hydropower | 4.778593 |
| Nuclear | 0.273086 |
| Oil | 7.141098 |
| Natural Gas | 52.92641 |
| Coal | 145.146 |
| Wind Energy | 0.533075 |
| Solar | 2.194819 |

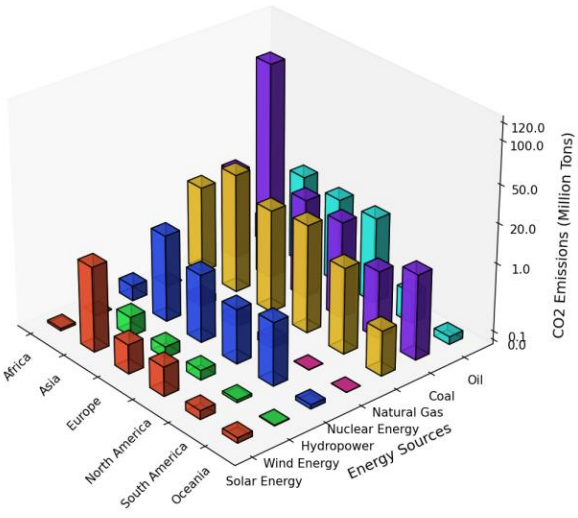

**Figure 3.** The carbon emissions of each state using various energy sources

### 4.3 Future Trends and Projections

Using grey forecasting techniques, we projected the energy consumption and associated carbon emissions of high-performance computing (HPC) systems through the year 2025, with the detailed results presented in Table 3 and figure4. Although the proportion of certain energy sources, such as oil, is declining, the rapid increase in computing power of HPC systems has led to higher electricity consumption. Consequently, overall carbon emissions from energy consumption have risen, with natural gas and coal showing particularly significant increases.

As can be seen from Figure 5, the total electricity production is generally on an upwardtrend between 2023 and 2025, indicating a continuous increase in energy demand, while the en-ergy structure is gradually transforming towards clean energy. In terms of the overall trend, theuse of coal, though still dominant, shows a year-on-year decline, while natural gas and renewable energy gradually increase, especially the share of renewable energy increases significantlyin 2025, showing the trend of energy structure transitioning towards clean energy. The shareof nuclear energy and hydropower is relatively stable, while the reliance on oil gradually decreases. 'This suggests that the world is gradually reducing its reliance on fossil fuels, especiallyhigh-emission coal, and shifting towards greater investment in natural gas and renewable energyto achieve a more sustainable energy mix.

Considering the future development of high-performance computing, we will increase thepercentage of global electricity consumption by high-performance computing to 2%, and againusing the formula for calculating carbon emissions, we can get the following: the total carbondioxide emissions in 2024 will be 243.53 MT, which is an increase of 7.8 % , and the total carbondioxide emissions in 2025 will be 246.75 MT, which is an increase of 9.2 %.

**Table 4.** Forecasted electricity generation from various energy sources for the years 2024 and 2025

| Year | Hydropower (TWh) | Nuclear (TWh) | Oil (TWh) | Natural Gas (TWh) | Coal (TWh) | Renewables (TWh) | Total (TWh) |
|---|---|---|---|---|---|---|---|
| 2023 | 4240.1 | 2737.7 | 698.1 | 6746.3 | 10513 | 4748.4 | 29924.9 |
| 2024 | 4438.5 | 2801.0 | 647.7 | 6996.6 | 10364.2 | 5437.2 | 30949.9 |
| 2025 | 4493.7 | 2824.3 | 619.3 | 7162.3 | 10447.0 | 6215.2 | 32036.6 |

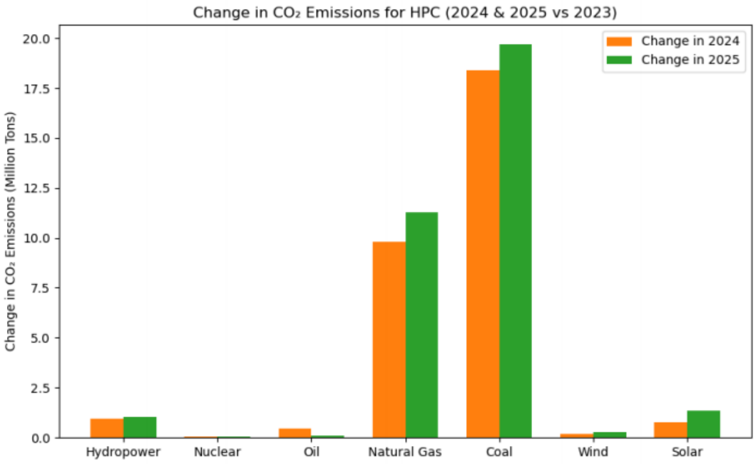

**Figure 4.** Change in $CO_2$ Emissions for HPC (2024&2025vs2023)

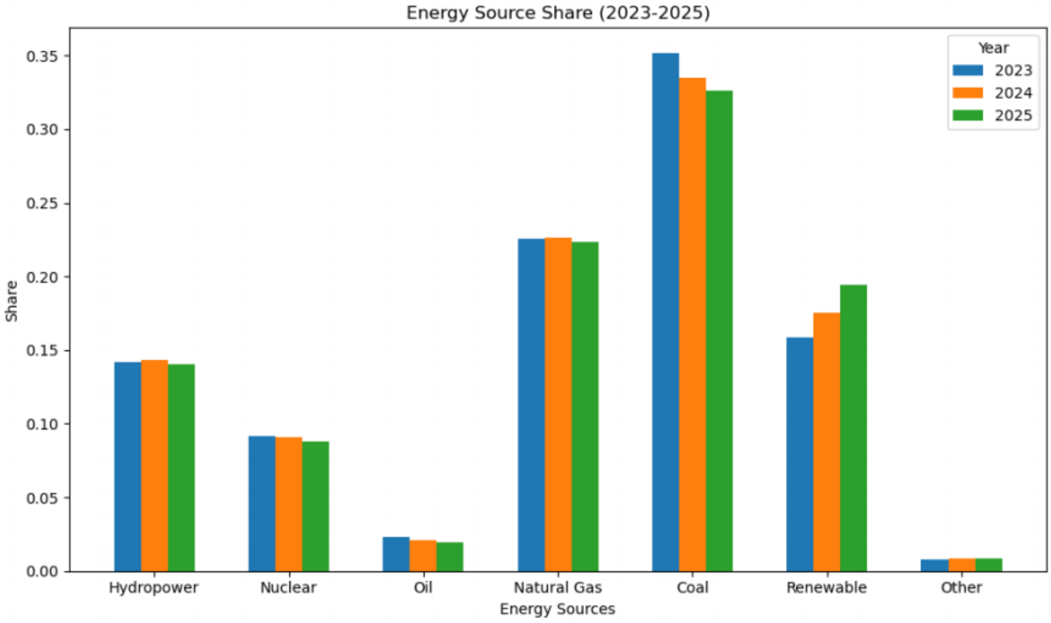

**Figure 5.** Share of different energy sources for three years

To thoroughly analyze the scope of the problem by 2030, we first projected the power generation from various energy sources for that year, with the specific results illustrated in Figure 6. The share of energy sources in electricity generation for 2030 is shown in Figure 7. Upon examining Figure 6, it is evident that the structure of energy power production is undergoing a significant shift. By 2030, compared to 2023, there is a clear trend toward reducing fossil fuels and increasing clean energy. The share of coal and natural gas has decreased, while the share of renewable energy has surged, indicating a gradual transformation of the energy structure toward a more environmentally friendly and low-carbon direction. The share of coal and natural gas decreases, whilethe share of renewable energy increases significantly, indicating a gradual transformation ofthe energy structure towards a more environmentally friendly and low-carbon direction. Mean.while, the share of hydropower and nuclear energy has remained largely stable, indicating thatthey remain reliable sources of energy in the power generation mix. These changes are in linewith global carbon reduction targets.

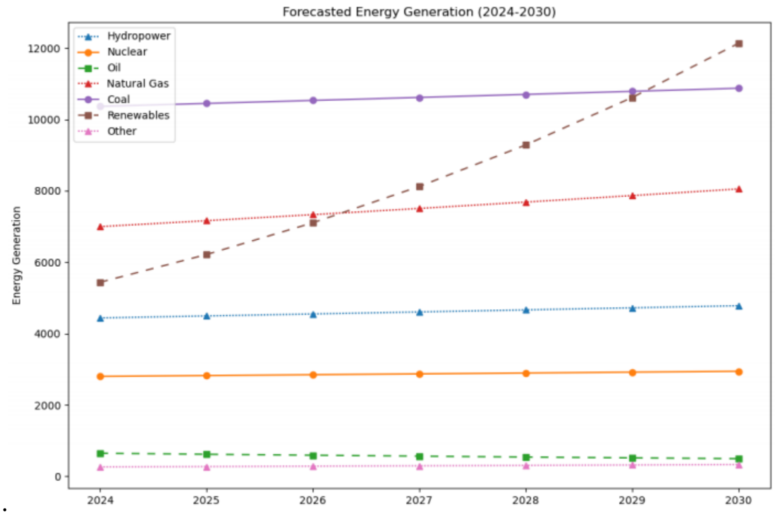

**Figure 6.** Forecasted Energy Generation (2024-2030)

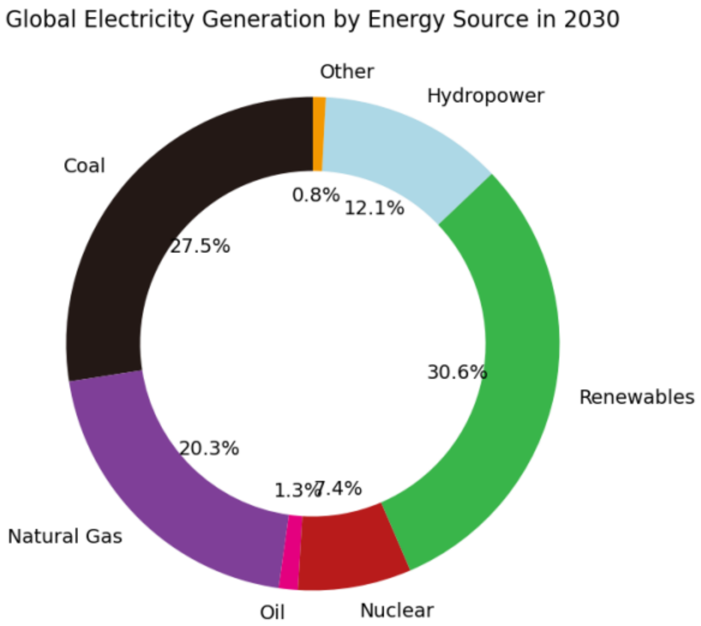

**Figure 7.** Global Electricty Generation by Energy Source in 2030

As illustrated in Figure 8, the analysis reveals significant shifts in the $CO_2$ emission shares of various energy sources between 2023 and 2030. The analysis of Figure 8 reveals significant shifts in emission source composition for high-performance computing between 2023 and 2030. First, coal's emission share demonstrates a marked decline by 2030, signaling a strategic transition toward cleaner energy alternatives and reduced reliance on carbon-intensive power generation. While natural gas and wind energy maintain consistent contributions to the energy mix throughout this period – maintaining their status as essential transitional and renewable energy sources respectively – solar and hydropower exhibit substantial growth trajectories. Particularly noteworthy is solar energy's accelerated adoption, which drives notable emission reduction through expanded clean energy utilization. Hydropower's increased participation further reinforces this sustainability trend. Meanwhile, nuclear energy persists as a stable baseline power source despite its modest market share, with other renewable sources showing minimal fluctuations. These patterns collectively illustrate an evolving energy landscape where diversified clean energy deployment progressively displaces traditional fossil fuels, while established transitional sources ensure grid stability during this transformation period [4].

Overall, the energy mix in 2030 is more environmentally friendly, reducing the proportionof high-emission energy sources such as coal and increasing the proportion of clean energ.sources such as solar and hydropower, which is in line with the goals of global carbon reductionand energy transition.

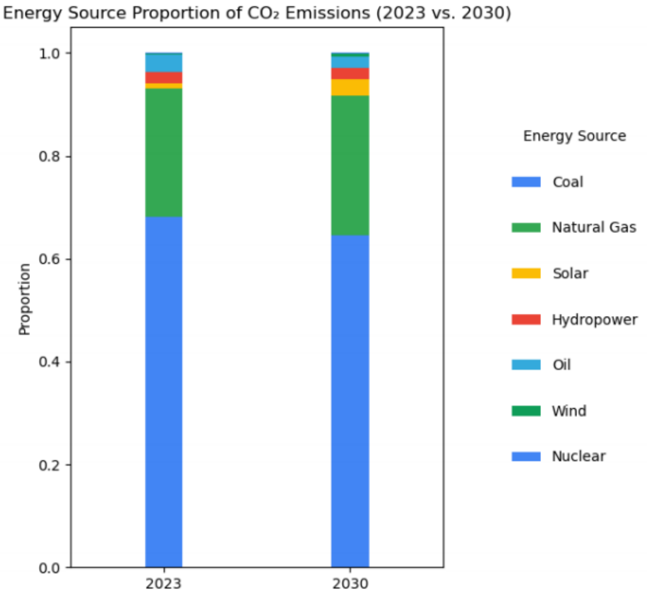

**Figure 8.** The changes in the different energy shares of $CO_2$ emissions between 2023 and 2030

### 4.4 Impact of Renewable Energy Transition

Renewable energy, derived from continuously replenished natural processes such as solar, wind, geothermal, hydro, tidal, and biogas, accounted for 30.1% of total electricity production in 2023. To assess the potential impact of increasing renewable energy's share, three scenarios were considered: (1) replacing 1 TWh of coal-generated electricity with 1 TWh of renewable energy; (2) replacing 1 TWh of natural gas-generated electricity with 1 TWh of renewable energy; and (3) reducing both coal and natural gas-generated electricity by 0.5 TWh each for every 1 TWh of renewable energy generated. The $CO_2$ reductions for these scenarios are illustrated in Figure 9, with the yellow line (coal replacement) showing the steepest reduction, the green line (natural gas replacement) the flattest, and the blue line (combined coal and natural gas replacement) in between. This trend is attributed to coal's higher carbon emission factor, making its reduction more impactful than that of natural gas, which has lower emission intensity.

By 2030, renewable energy is projected to generate 42.7% of the world's electricity, with hydro, wind, and solar contributing 28%, 33%, and 32% respectively. When 100% renewable energy is used for electricity production, hydro, wind, and solar are expected to each produce 30% of the total renewable electricity. Under this scenario, the carbon dioxide emissions from hydro, wind, and solar power generation are estimated at 11.24175 MT, 2.286753 MT, and 13.33649 MT respectively, resulting in a total emission of 26.865 MT—a significant reduction compared to fossil fuel-based generation. Hydro and solar are projected to be the primary sources of electricity, highlighting renewable energy's substantial potential for reducing carbon emissions.

However, achieving 100% renewable energy poses several challenges. First, balancing supply and demand is critical, as solar and wind power are subject to weather, seasonal, and diurnal variations, while hydropower is affected by climate and drought. Ensuring a stable 24-hour power supply requires advanced energy storage systems to address these intermittencies. Additionally, the high upfront costs associated with large-scale energy storage, grid upgrades, and distributed generation infrastructure must be managed. Despite these challenges, the transition to renewable energy remains a crucial step toward a sustainable and low-carbon future.

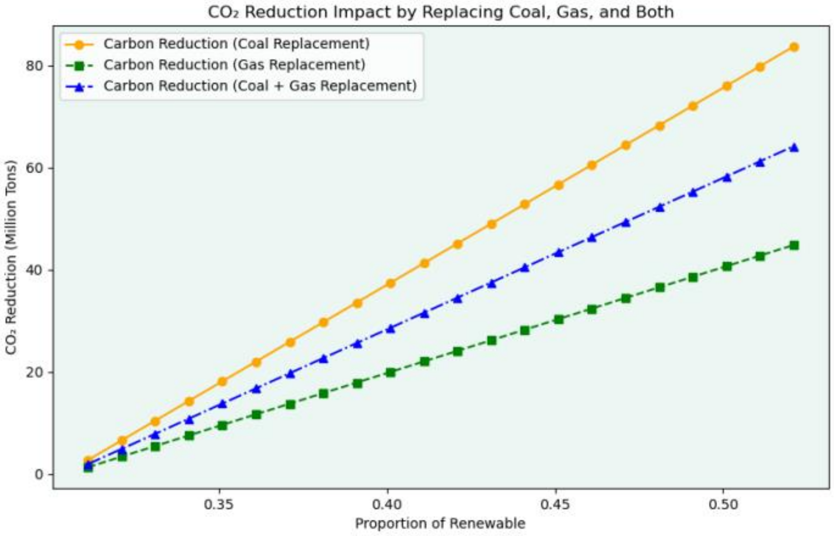

**Figure 9.** $CO_2$ Reduction Impact by Replacing Coal, Gas, and Both

### 4.5 4Environmental Impact of Wastewater Discharge

Our calculations using this methodology yielded scores for the years 2023 to 2028 as shown in Table 4.In this case, the closer the rating value is to 1, the lower the environmental impact of HPCin that year. Therefore, it can be obtained that as the year grows, the carbon and pollutantemissions of high-performance computing have less impact on the environment.

**Table 5.** Topsis scores from 2023 to 2030

| 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|
| 0.000 | 0.237 | 0.506 | 0.710 | 0.852 | 0.859 | 0.734 | 0.531 |

## 5. Discussion

This study analyzes the energy consumption, carbon emissions, and broader environmental impact of high-performance computing (HPC) systems from multiple dimensions and perspectives, and comprehensively analyzes their current status and future development direction. A detailed analysis of global electricity consumption data shows that data centers, especially those that support HPC operations, currently account for about 1.5 to 2 percent of global electricity use. This percentage rises even further when operating at full capacity, indicating that these systems are extremely energy-intensive. HPC energy consumption accounts for a large portion of global CO2 emissions of around 212.99 million tonnes, especially in regions such as Asia. This illustrates the challenges that energy consumption and carbon emissions from HPC systems may pose to achieving global carbon reduction targets, and predicts that CO2 emissions will continue to rise in the coming years without active interventions.

This study explores whether the shift in energy conversion type will have an impact on the carbon emissions of equipment related to HPC operation. The results show that renewable clean energy technologies such as wind, solar PV and hydropower have significantly lower carbon emissions compared to traditional fossil fuel power generation. However, the current operation of HPC-related equipment still relies mainly on traditional energy sources, especially coal and natural gas. Projections suggest that the integration of renewable energy sources has the potential to reduce carbon emissions from the operation of HPC-related equipment by 40 to 60 percent. However, HPC faces significant technical and economic challenges in reducing carbon emissions. By adopting energy-efficient technologies, renewable energy, and efficient cooling systems, green data centers can be built to reduce the carbon footprint of HPC systems.

The environmental impact of high-performance computing (HPC) systems goes beyond carbon emissions, water consumption and wastewater discharge. In this study, the entropy-weight method combined with the TOPSIS method was used to analyze the environmental impact associated with HPC systems. The study found that although the water-cooled system widely used in HPC centers showed good cooling efficiency, there was a large amount of water consumption during operation and posed a risk of water pollution. Technological advances and the gradual integration of clean energy sources can help reduce the environmental impact of HPC systems. At present, the world is facing problems such as water shortage, climate warming, and air pollution, and the energy consumption of HPC systems is closely related to them. To reduce the environmental impact of HPC, this study builds models to enhance energy efficiency and reduce carbon emissions by adopting anhydrous liquid cooling solutions, implementing dynamic power management frameworks, and deploying advanced workload allocation algorithms. Align advances in HPC technology with global environmental management goals without compromising system performance integrity.

However, there are still some limitations to this study. The study is based on the assumption that the energy mix will remain unchanged in the next few years, but in reality, technological progress and policy interventions are due to real-time changes, and the actual changes cannot be fully simulated under such assumptions. For example, with the current development of technology, rapid progress in renewable energy technology or changes in energy-related policies may significantly change the energy structure, which will affect the energy consumption and carbon emissions of high-performance computing (HPC) systems. In addition, the model used in this study is primarily based on historical data. Historical data is only representative of the past and cannot simulate the potential impact of future technological breakthroughs or market changes on HPC energy consumption and emissions. The advent of new energy-efficient computing techniques or changes in the global energy market will have an impact on the model, so relying solely on historical data may limit the accuracy of the model's predictions.

Based on the above limitations, by further exploring emerging technologies such as quantum computing and artificial intelligence, we aim to reduce the environmental impact on HPC systems, with a view to changing computing efficiency and energy management in HPC environments.For example, through server virtualization, cloud computing and other technologies, hardware utilization can be improved, thereby reducing energy consumption. Server virtualization technology allows a physical server to be divided into multiple virtual machines, thereby improving hardware utilization and reducing energy consumption. By optimizing the environment of the data center, energy consumption can be reduced. For example, energy consumption can be reduced by increasing the temperature and humidity of a data center. Energy consumption can also be reduced through the use of energy-efficient lighting. Renewable energy sources such as solar and wind power are used to power HPC systems, reducing dependence on traditional energy sources and reducing carbon emissions. At the same time, through the intelligent energy management system, the efficient use and dispatch of energy can be realized.

The energy efficiency revolution in high-performance computing is a journey full of challenges and opportunities. In this revolution, we need to constantly explore new technologies and methods to balance the relationship between computational speed and sustainability. Only in this way can we promote scientific and technological progress while protecting the planet on which we live.

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