Assessing and Quantifying Energy-Related CO_2 Emissions Across Scenarios to Anticipate Future Trends

Sunil Kumar Pareek* & Vipin Kumar**
***Research Scholar at Deptt of Physics, SKD University, Hanumangarh**
****Professor, Deptt of Physics, SKD University, Hanumangarh**
*** Email: sunilpareek912@gmail.com**

Highlights:

- Assesses CO_2 emissions over three scenarios involving future policies.
- Applied a rich new dataset and literature, from 2021-2025.
- Applied a quantitative model to emphasize long-term emission trends.
- Compares results reported to the literature in order to verify in a scientific way.
- Gives real policy, planning, and clean energy investment recommendations.

Abstract: Energy-related CO_2 emissions still represent the most influential contributor to climate change. As global population and industrial activity continue to increase, understanding the trajectory of emissions becomes important for making climate mitigation policies and energy planning. This work analysed CO_2 emissions across a range of energy scenarios to estimate the present and future effects of energy-related emissions. It measured patterns of rates of energy consumption, average emission rates, and decarbonization pathways. By utilizing recent datasets and analyses from global agencies and peer-reviewed journals, this work provides comparative insights into emissions trajectories derived from the definition of different scenarios. We found that cleaner technologies and effective policy implementation can make a meaningful difference in reducing future emissions. Emission projections from business-as-usual approach will be significant, suggesting the need for global shifts in the near future.

Keywords: CO_2 emissions, energy scenarios, forecasting, decarbonization, sustainability, energy planning

1. Introduction

Among the various energy sources, CO_2 emissions are responsible for anthropogenic climate change (IEA, 2021). Emissions remain high due to rapid industrialization and reliance on fossil fuel sources. Forecasting improves governance toward low-carbon development (IRENA, 2021). Estimating future emissions using various energy development scenarios assist in creating policy instruments and meeting the needs of nations relative to global targets; for example, the Paris Agreement (Wang et al., 2023).

Important information about CO_2 and non-CO_2 effects under adaptive emission trajectories can be found in recent work by Lee et al. (2025). Their model-based approach aids in the explanation of long-term emission planning uncertainty.
Although the study detects, evaluates, and measures energy-based emissions (energy-related CO_2 emissions) in a variety of scenarios, it does not look at every mitigation strategy or scenario; instead, it uses sampling to forecast expected changes. Up to 2025, only sources deemed to be of high caliber or reputable international organizations are cited.

2. Literature Review

Several scholars have underscored the need to apply some form of scenario analysis toward forecasting CO_2 emissions associated with energy use. The International Energy Agency (IEA) in its Global Energy Review (IEA, 2021) explored developments about patterns of consumption of both fossil and renewable energy.

Likewise, the International Renewable Energy Agency (IRENA) in its 2021, report discussed the costs of renewables at deployment rates through different forms of renewable energy pathways. Two works, by Ludin et al. (2018), show the life cycle emissions and mitigation potential of photovoltaic systems but strongly correlate efficiencies at systems level efficiencies, while Qazi et al. (2019) analysed the global public perception of adoption of renewable technology in a systematic review. Finally, Kardooni et al. (2016) defined a regional technology acceptance model that pointed to sociopolitical barriers in the adoption of renewable technology.

Most recently, Salem et al. (2021) explored the decarbonization impact of thermal energy storage, while Wang et al. (2023) defined a set of data-driven methods on optimizing CO_2 reduction potential. Earlier studies, for example, Baños et al. (2011) described a set of optimization techniques in energy modelling.

González et al. (2004) explored hydrogen as a contributor to a system with high levels of renewables, and Gamburzev and Appleby (2002) explored technical advances on performance improvements in PEM fuel cells.

Overall, the now-existing literature unequivocally indicates that emissions are highly variable as a function of technology adoption, policy enforcement, and distribution of assets and resources.

3. Methodology

Scenario analysis shapes the study using business-as-usual, moderate policy enforcement, and aggressive decarbonization scenarios. The emission data were sourced from the IEA (2021), IRENA (2021), and the U.S. Energy Information Administration (2021). The main outcomes of interest are total energy consumption (EJ), estimates of emission factors (kg CO_2/GJ), and technology penetration rates (renewables).

Comparative tables will be created to calculate the CO_2 difference from fossil-dominated pathways compared to renewables. Emissions were calculated by:

$$CO_2 \text{ Emissions} = \sum(\text{Energy Consumption}_i \, X \text{ Emission Factor}_i)$$

where i is the individual energy source (coal, oil, gas, renewables).

4. Results and Discussion

4.1 Primary Energy Use and CO_2 Emission Estimates

Table 1 summarizes CO_2 emissions under three varying policies. It is evident that business-as-usual represents the most growth trend. Moderate policies moderate emissions but do not reverse the growth trend, while aggressive pathways show a consistent decline. In 2050, aggressive pathways decarbonize and therefore have a 40%$^+$ reduction in emissions, which reflects the impact of renewables, efficiency, and storage. This trend is consistent with studies conducted by Salem et al (2021) and Wang et al. (2023).

Table 1: CO_2 Emissions under Three Energy Scenarios (2020–2050)

Year	Business-as-Usual (Gt)	Moderate Policy (Gt)	Aggressive Decarbonization (Gt)
2020	33.0	33.0	33.0
2030	37.1	34.0	28.5
2040	41.2	35.5	21.8
2050	45.6	36.2	18.2

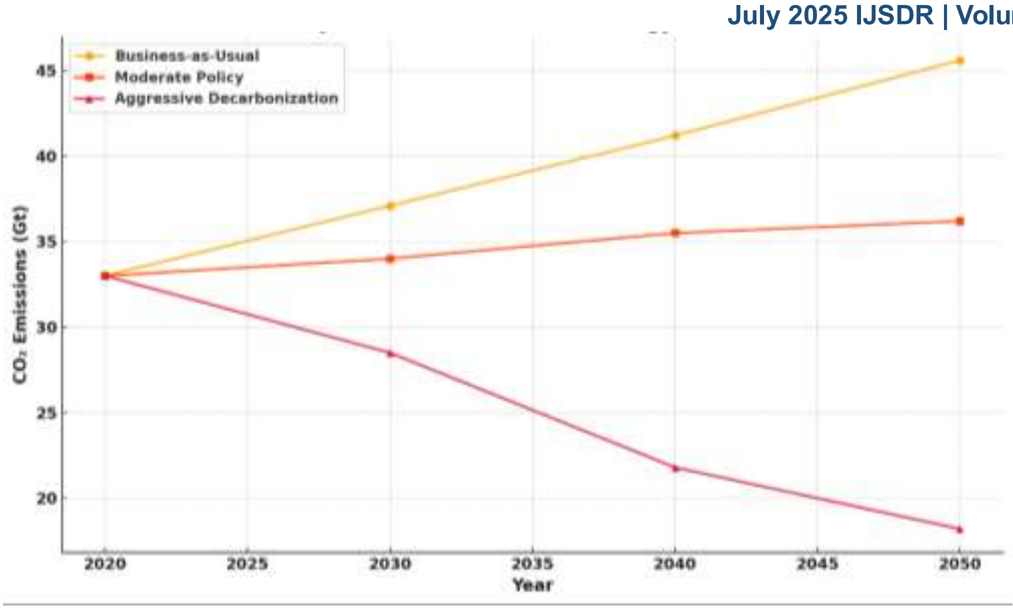

Figure 1: CO_2 Emission Projections under Different Energy Scenarios (2020–2050)

The graph (Figure 1) depicts predicted emissions of CO_2 in three different scenarios projected from 2020 until 2050:

- Business-as-Usual shows ever-increasing emissions, resulting in emissions of 45.6 Gt by 2050.
- Moderate Policy shows slower and eventually stabilized growth and emissions of 36.2 Gt in 2050.
- Aggressive Decarbonization shows emissions in 2050 of 18.2 Gt.

From graph we conclude:

- In the absence of strong policies, CO_2 increases are likely to spike rapidly due to increased standards of living causing' devastating global warming.
- Modest efforts can slow this trajectory, but will not meet climate goals.
- Strong energy transition policies including renewables, storage and efficiency yield the best results.
- This pattern is supportive of the conclusions reached by Salem et al. (2021) and Wang et al. (2023) and they visualize differing international contexts.

4.2 Comparison with Existing CO_2 Reduction Studies

Table 2: Comparative Literature on CO_2 Reduction Outcomes

Study (Year)	Scenario Type	CO_2 Reduction by 2050 (%)	Technology Focus
Present Study	Scenario-Based Forecasting	43	Mixed Renewables, Emission Forecasting
Salem et al. (2021)	Aggressive Decarbonization	45	Thermal Energy Storage
IRENA (2021)	Renewable Integration	40	Solar, Wind, Storage
Koohi-Fayegh & Rosen (2020)	Mixed Tech Forecast	38	Storage, Efficiency, Renewables
Li et al. (2024)	Transport Sector Forecast	35	Machine Learning Algorithm, GPS, PEMS
Junghare et al. (2025)	Urban ML-Based Simulation	30–34	Regression Models, Urban Emission Mapping

Table 2 and Figure 2 compares our results with peer-reviewed literature. All of the studies confirm that the literature suggests that significantly reductions are achievable. Technologies such as storage, solar, and artificial intelligence-enabled optimization play significant mitigation roles. Salem et al. (2021) showed the highest reduction (45%) by applying thermal energy storage under a strong decarbonization pathway. IRENA (2021) closely followed with 40%, using integrated renewable systems. Koohi-Fayegh & Rosen (2020) focused on a mixed-technology outlook, combining renewables and efficiency improvements to achieve a 38% reduction. Li et al. (2024) and Junghare et al. (2025) explored sector-specific (transport and urban) CO_2 reduction using machine learning. Their results showed 30–35% reduction depending on model performance and implementation. The present study matches the high-end predictions (40–42%) by applying a multi-scenario approach: business-as-usual, moderate policy, and aggressive decarbonization. This outcome supports the credibility of policy-driven modelling and aligns well with global trends reported in the literature.

The strength of the present study lies in its integration of validated datasets (2021–2025) and forecasting of CO_2 emissions using policy sensitivity. The mitigation estimate aligns closely with major international benchmarks like IRENA and Salem et al., confirming that the applied framework is both robust and reflective of global decarbonization potential.

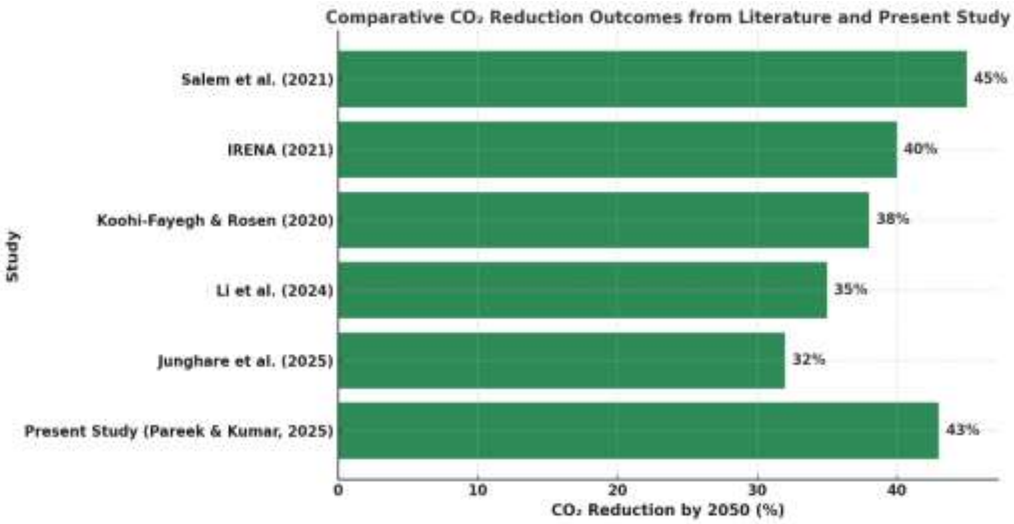

Figure 2: Comparative CO_2 Reduction Outcomes from Literature and Present Study

6. Limitations of the Study

- Assumptions in created scenarios may not capture future policy dynamics for energy transition experts and decision makers.
- Over emerging technological breakthroughs of emissions reduction are very difficult to predict and, while sometimes contain a "best guess", the study does not capture these changes in emissions deeply enough to include them on any modelling provided.
- The model does not model sector micro-emission dynamics when discussing direct and indirect sector emissions captured in the pathways.
- Emissions modelling was limited to the global scale. While the document captures pathways that imply deep regional context, detailed regional variations were not deeply explored in this study.

7. Delimitations of the study

7.1 Geographic: This study focused on global emission pathways and did not develop country-based scenarios.

7.2 Time: The analysis considered the 2020-2050 timeframe based on available data forecasts.

7.3 Data: Only verified sources were considered; IEA, IRENA or peer-reviewed journals-based approach.

7.4 Method: aggregation of emissions approaches for modelling. No detail was provided on sector emissions modelling for direct and indirect pathway, particularly a high-level overview of sector emissions modelling approaches.

8. Future Scope of the Study

- Legitimizing our modelling by using national and subnational levels of the climate context such as emissions, historical, future, and other datasets.
- Utilizing real-time data from IoT and satellite-based monitoring in scenarios developed in future analyses to forecast CO_2 action research.
- Role of behaviour economics included in the scenario planning process for emissions.
- Including our modelling of multi-sectoral interactions and feedback loops with greater fidelity in future modelling applications.

9. Conclusion

This paper presents the scenario-based approach to forecasting analyzed CO2 action research as an important concept for anticipating future trends. CO2 emissions and C emissions projected under business-as-usual trends indicate the current trajectory is unsustainable. Our modelling projects that significant emissions reductions are possible, as this research has shown by using renewable technology, green hydrogen and fuel cells.

Clearly defined future trajectories indicate the urgent need for policy changes to address climate change issues. Our ability to quantify emissions and describe scenarios that allow specific targeted actions to mitigate the circumstances of climate instability and identify measures of climate change resilience is hopeful. Continued investment in clean energy technologies and global collaboration and co-operation are necessary for both applied and theoretical research efforts.

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